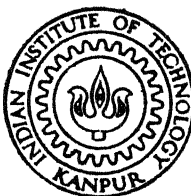


THERMO-ANALYTICAL / NON-ISOTHERMAL STUDIES ON DECOMPOSITION OF CALCIUM CARBONATES

by

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DEPARTMENT OF METALLURGICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY, KANPUR
DECEMBER, 1981

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THERMO-ANALYTICAL / NON-ISOTHERMAL STUDIES ON DECOMPOSITION OF CALCIUM CARBONATES

A Thesis Submitted
In Partial Fulfilment of the requirements
for the Degree of
MASTER OF TECHNOLOGY

by
D. M. A. KHAN

to the
DEPARTMENT OF METALLURGICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY, KANPUR
DECEMBER, 1981

Case No. 70561

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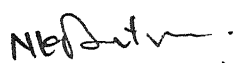
D E D I C A T E D T O M Y M O T H E R

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C E R T I F I C A T E

This is to certify that the thesis entitled 'THERMO-ANALYTICAL/NON-ISOTHERMAL STUDIES ON DECOMPOSITION OF CALCIUM CARBONATES' submitted by Mr. D.M.A. Khan, in partial fulfilment of the requirements for the Degree of Master of Technology at the Indian Institute of Technology, Kanpur is a record of bonafide research work carried out under my supervision. The work embodied in this thesis has not been submitted elsewhere for a degree.

Date : 28-12-81.


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1.1.82



ACKNOWLEDGEMENTS

I wish to express my sincere and humble gratitude to Dr. H.S. Ray and Dr. N.K. Batra for their invaluable guidance.

I thank Bokaro Steel Plant for supplying the necessary limestone and dolomite samples for PTA work. My thanks are to UTMAL, Kansbahal authorities for their good drawings and prints. I thank Mr. Bharatmal of Material Science Department for his PTA prints and Central Glass blowing section for supplying the necessary apparatus within appropriate time.

I am obliged to Mr. D.P. Tripathi and Mr. Awadesh Sharma, Technical Assistants for their help and co-operation. My thanks are to Metallurgical Engineering Department Office and Staffs for allowing me to use their typewriter for typing. I would like to acknowledge the helps rendered to me by my friends throughout this work.

D.M.A. Khan

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A B S T R A C T

This thesis describes about an investigation on the dissociation behaviour of a large number of samples of calcite, limestone and dolomite available in the laboratory or obtained from the industry. The industrial samples represent raw materials from different mines. The work has three main parts,

- (a) Development of various laboratory techniques to be applied in the investigation of decomposition reaction.
- (b) Actual studies on various samples and collection of data.
- (c) Analysis of all experimental data for quantitative assessment of the mode of decomposition and thermal properties of samples and an attempt to correlate the data obtained using different techniques.

The emphasis of the work is on the development of the experimental techniques and methodology. The experimental data have been primarily used to establish the validity of the techniques proposed and used. However, an attempt is also made to generate some decomposition data which may be of interest to the industries.

The experimental techniques described include the following,

- (a) Thermal analysis of samples (simultaneous DTA, TG, DTG).
- (b) A new technique called the 'Moving Bed' technique in which a bed length of sample is gradually introduced into a furnace hot zone and decomposition allowed to

take place under rising temperature condition.

- (c) Continuous measurements of temperature of volume elements of a moving bed to understand the heating characteristics of materials flowing into a furnace with time.
- (d) Measurement of the rate of rise of temperature of samples (initially at room temperature) suddenly introduced into the hot zone of furnace at a constant temperature.
- (e) Continuous measurement of evolution of carbon di-oxide generated by decomposition of a sample kept at the furnace hot zone at a given temperature. A special bleeding device is provided to maintain a given carbon di-oxide pressure in the system during decomposition.

CHAPTER I

INTRODUCTION

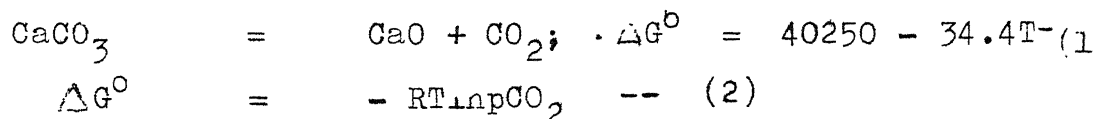
1.1 General :-

Limestone is recognised as an important raw material for the manufacture of Iron and Steel. It also finds use in the manufacture of portland cement, in agricultural purposes etc. An average of 0.3 ton or more of limestone flux is required to produce one ton of pig iron in blast furnace to combine principally with silica and alumina to form low melting point slags and to provide slag basicity to control silicon, sulphur and manganese levels in the molten metal. In steel making, calcined lime is normally used as fluxing material. Limestone additions in the open hearth process gives rise to lime boil which effectively stirs the bath and brings the lime to slag where it replaces the oxides of iron and keep sulphur and phosphorus level low. In modern rapid oxygen converters lime quality plays a critical role as it must dissolve in the slag rapidly for better control of sulphur and phosphorus. In de-oxidation of steel de-oxidising power of ferro alloys is improved by presence of CaO in the slag.

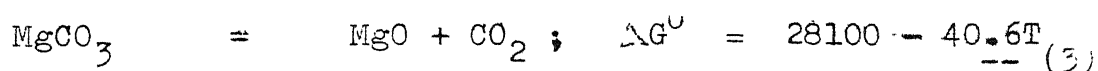
Dissociation behaviour of limestone in the burden affects the performance of blast furnaces [1]. Dissociation behaviour is also important in the calcination operations in the kiln or shaft to produce lime. It is thus important to study the decomposition behaviour of limestone.

1.2 Thermodynamics of Limestone dissociation : -

Reliable thermodynamics data for limestone decomposition are available in the literature [2]



where ΔG° is the standard free energy change for the reaction, $p\text{CO}_2$ is the partial pressure of CO_2 and T is the temperature in $^\circ\text{K}$.



It may be readily shown that MgCO_3 decomposes at a temperature of 420°C and CaCO_3 at 900°C at $p\text{CO}_2$ of 1 atm.

In the case of dolomite the dissociation reaction would involve two sequential steps. MgCO_3 in dolomite decomposes first followed by CaCO_3 . Often these sequential steps overlap

1.2.1 Dissociation behaviour of actual Calcium carbonates :

For Calcite, dissociation temperature is 898°C [3,4] at 1 atm. Magnesium carbonate dissociates at a much lower temperature i.e. 420°C at $p\text{CO}_2$ of 1 atm. Since the proportion of MgCO_3 and CaCO_3 differs in many species of dolomitic and magnesian limestone, the dissociation temperature naturally varies. These cannot be calculated from theory and actual experiments alone can give the data. In most cases the MgO is hard burnt in varying degrees before CaO is formed. Even if the CaO constituent is soft burnt the hard burnt MgO component influences a denser quick lime of lower reactivity than a comparably calcined high calcium lime.

According to Hedin [5], certain kinds of limestone cannot successfully calcined into lump or quick lime. These types may largely dissociate into oxide but they will decrepitate into small fractions down to dust rendering the product unsuitable for many uses and seriously complicating the process of calcination. Large crystalline forms are most prone to behave like this and experimental calcination of the stone is judicious before a plant investment is made. This is 'physical oddity' and the chemical analysis of the stone has little or no influence on this characteristics.

Fostel [6] also observed that the CaCO_3 crystal lattice, in preheating undergoes thermal expansion of 5 to 10pct. prior to calcination. A residual effect of this expansion is an increase in the stones porosity.

1.3 Non-isothermal kinetics :-

During heating a carbonate may decompose continuously and therefore, the dissociation reaction is essentially a nonisothermal. Such reactions can be studied by thermal analysis under rising temperature conditions. Dynamic nonisothermal kinetic studies are carried out by allowing a reaction to take place at progressively higher temperature using a welldefined temperature time relationship, progress of the reaction being recorded (eg. as weight change) against temperature or time.

Traditional kinetic studies involve a series of runs in which a reaction takes place under 'isothermal conditions'.

From the plot of fraction decomposed i.e. ' α ' against time ' t ' a reaction rate constant is derived by expressing weight as an appropriate function of ' t '. If the experiment is then repeated at several other temperatures and an unchanged reaction is assumed then an Arrhenius type plot can be obtained and the activation energy calculated. Such isothermal experiments generally yield a value of about 50 Kcal/mole [7] for the activation energy of limestone.

The isothermal experiments require large number of runs. Moreover it is always difficult to attain a fixed temperature without some pre-reaction. Therefore an uncertainty remains regarding zero time of reaction. Also it is very difficult to reproduce physical characteristics of a sample in every run.

The commercial thermal analysis equipments use very small samples to ensure thermal equilibrium with the furnace. It is however possible to design a technique for thermogravimetry on large masses. The technique is described in detail later.

1.4 Differential Thermal Analysis (DTA), Thermogravimetry(TG) and Derivative Thermogravimetry (DTG)

DTA measures heat effects in a system due to phase changes or reactions. DTA studies have found wide applications in various fields. It is, however, now realized that more useful information is obtained when DTA is combined with TG and DTG. In TG the weight of the sample is measured continuously and the course of the reaction is followed through measuring weight changes.

DTG gives the rate of change of weight loss and gives a measure of reaction rate at various temperatures. The modern approach in thermal analysis therefore is simultaneous DTA, TG and DTG studies. The principles of these techniques are well known and therefore will not be discussed here.

1.5 Aim of the present Investigation :-

The present work is aimed at studying decomposition behaviour of a large number of calcite, limestone and dolomite samples using various techniques of thermal analysis. The techniques include DTA, TG, DTG and a new method called 'Moving Bed' technique which is suitable for studying the decomposition behaviour of large samples. They are described in detail in subsequent chapters.

The data obtained using various techniques are to be analyzed to establish an overall comparison of the decomposition behaviour of various samples.

C H A P T E R I I

P L A N O F T H E W O R K

The present work is aimed at comparing the dissociation behaviour of various grade samples of calcite, limestone and dolomite under Isothermal/Non-isothermal experimental conditions. The work is contemplated in the following manner.

2.1 DTA Technique :-

DTA technique is suitable only for very small samples (10 to 500 mg) to investigate exothermic or endothermic reactions taking place in the system. TG shows whether the reactions involve weight changes or not. DTG gives additional kinetic data for the reaction by providing the slope values of TG curve. A standard 'Derivatograph' instrument was used for simultaneous measurements of DTA, TG and DTG of the samples.

First the effect of parameters such as particle size, heating rate, gas flow rate etc. was established. Subsequently all studies were done under standardized conditions so that the experimental data become amenable for comparative analysis. A series of experiments were also conducted to study sequential decomposition reactions such as those found in a combination of carbonates. The effect of the nature of association of carbonates was studied.

2.2 Moving bed technique :-

This method describes a generalized approach on non-isothermal kinetic investigations which use large samples and non-

linear heating programme. It proposes a moving bed experiment in which a large volume of sample is spread in a long quartz tube and the tube is introduced into a furnace hot zone at uniform speed. When the boat is withdrawn, it gives a series of successive volume elements which have been subjected to a temperature-time programme for different periods.

The heating programme would depend primarily on the temperature profile of the furnace, the boat speed and the heat transfer co-efficient. The temperature-time plots can be obtained by thermocouples positioned in the moving bed for several samples. The results of such findings established non-isothermal kinetic data for a known heating programme. It was then possible to compare the dissociation of large and small samples.

2.3 Measurement of evolution of Carbon di-oxide :-

An apparatus was set up to measure the flow rate of liberated CO_2 gas which in turn could be related to the amount of material decomposed at any time of heating. Variables studied in such experiments include temperature, CO_2 pressure, particle size, different grade of materials etc.

In some experiments simultaneous temperature and carbon di-oxide measurements were carried out to give additional information on the decomposition behaviour of samples.

CHAPTER III

EXPERIMENTAL

3.1 Materials :-

For thermal analysis most of the samples were obtained from Bokaro Steel Limited, Bokaro (samples of limestone and dolomite) brought from the sources such as Kuteshwar, Satna, Chopan, Birmitrapur, Baradwar, Ramtek etc. Double carbonates of $\text{Na}_2\text{CO}_3 \cdot \text{CaCO}_3$ were synthesized in the laboratory. Calcite and locally available limestone and dolomite materials were procured and chemically analysed in the laboratory and the compositions are given in Table III-1. Analytical grade of CaCO_3 and MgCO_3 with purity of almost 99 pct. were also used in some studies.

Unless otherwise mentioned the average particle size of the samples used was 75 μ (micron) i.e. -90 μ to +63 μ for DTA. In all other cases the actual sizes used are mentioned with all experimental data.

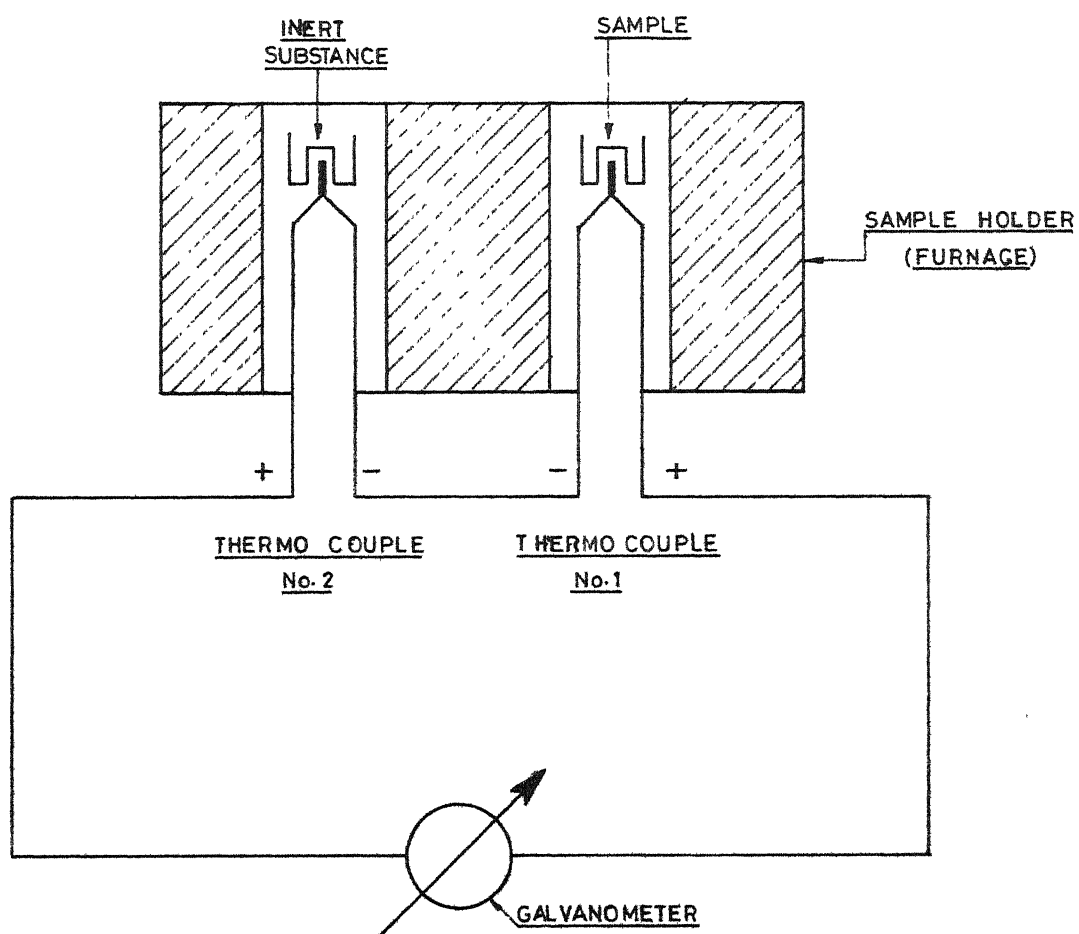
3.2 Equipments :-

3.2.1 Derivatograph :

The line sketch of the Derivatograph is shown in fig.(1) [8,9]. In the DTA cell there are two thermocouples interconnected through a galvanometer. One crucible holds the reference material Al_2O_3 (Alumina) and the other holds the test sample. The two crucibles are heated in a furnace. There is provision for flushing the system with inert gas argon at a controlled flow rate. The equipment offers various sensitivities and various rates of heating are available (e.g. 5°, 10°, 25°, 30°C/min.)

T A B L E III - 1
CHEMICAL ANALYSIS OF SAMPLES AFTER COMPLETE BURNING
AT 1000°C

| Compounds | Calcite | Limestone | Dolomite |
|--------------------------------|---------|-----------|----------|
| | pct. | pct. | pct. |
| CaO | 98.57 | 84.34 | 70.42 |
| MgO | .. | 4.72 | 24.51 |
| SiO ₂ | 1.27 | 6.13 | 1.31 |
| Fe ₂ O ₃ | 0.16 | 4.01 | 2.61 |
| Al ₂ O ₃ | .. | 0.74 | 1.14 |



FIG(1) LINE SKETCH OF DERIVATOGRAPH

3.2.2. Moving bed and other Experiments:-

For moving bed and CO_2 evolution studies, a kanthal wound resistance furnace was employed. A sketch of the apparatus is shown in fig.(2). The temperature was controlled with an accuracy of $\pm 5^\circ\text{C}$ with the help of a temperature controller. Actual temperature was measured using a Chromel-Alumel thermocouple connected to a potentiometer. The rate of evolution of CO_2 was controlled through a mercury bubbler device shown in fig.(3). and by using a capillary flowmeter.

3.3 Experimental Procedure :-

3.3.1 DTA/TG/DTG plots :

About 400 mg of the sample was taken in a standard ceramic crucible and kept above Thermocouple No.1. Inert Al_2O_3 sample was taken in the other crucible and kept above the thermocouple No.2. The standard flow rate of argon was 1cc/min. DTA, TG and DTG plots were plotted simultaneously. The details of the experimental conditions for the thermal analysis studied in the present work are given in Table-III-2.

3.3.2 Moving bed technique :

About 100 gm of calcite in the size range of -5 to +14 mesh were dried in an oven and kept inside a 60cm long, 1.4cm I.D., quartz tube which was sealed from one end. The tube was then pushed inside the furnace at the rate of 1 cm/min or 1/2 cm/min for a predetermined period of time, removed and allowed to cool in air. The material was sampled from various distances along the length of the tube for further analysis by reheating the volume elements individually at 1000°C for 90 minutes.

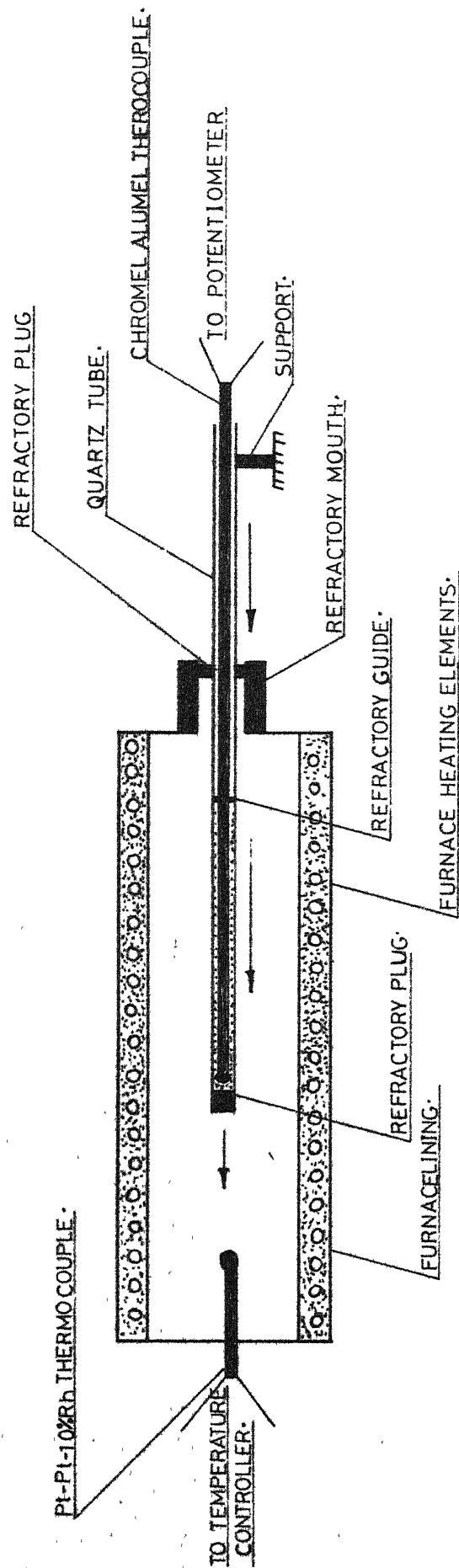


FIG.(2) SCHEMATIC DIAGRAM OF
MOVING BED APPARATUS.

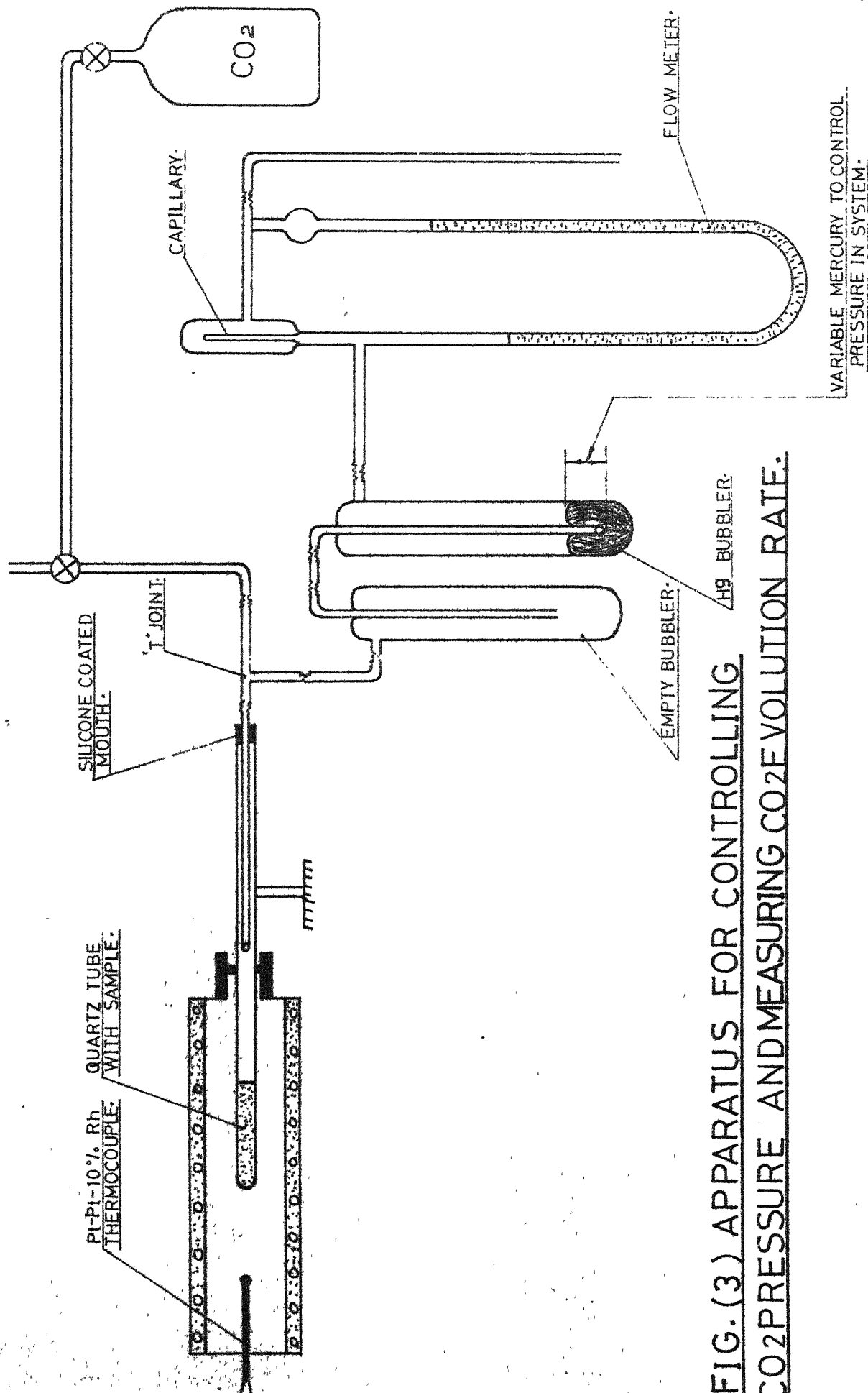


FIG. (3) APPARATUS FOR CONTROLLING
CO₂ PRESSURE AND MEASURING CO₂ EVOLUTION RATE.

T A B L E III - 2

DETAILS OF EXPERIMENTAL CONDITIONS FOR DIFFERENTIALTHERMAL ANALYSISArgon Flow Rate = 1 cc/min[pCO₂]_{bulk} = 0

| Sl.No. | Run No. | Sources | Particle size | Actual Weight | Heating Rate |
|--------|---------|---|------------------------|---------------|--------------|
| 1 | DT1 | L/S Kutahwar | -90 μ to +63 μ | 396 mg | 25°C/min |
| 2 | DT2 | L/S Satna | " | 400 mg | " |
| 3 | DT3 | L/S Chopan | " | 400 mg | " |
| 4 | DT4 | L/S Birmitrpur | " | 394 mg | " |
| 5 | DT5 | Dolo Baradwar | " | 400 mg | " |
| 6 | DT6 | Dolo Ramtek | " | 400 mg | " |
| 7 | DT7 | Dolo Chopan | " | 388 mg | " |
| 8 | DT8 | Mech. mix. | " | | " |
| | | CaCO ₃ - MgCO ₃ | " | 400 mg | " |
| 9 | DT9 | Na ₂ CO ₃ ·CaCO ₃ | " | 400 mg | " |
| 10 | DT10 | Mech. mix | " | | " |
| | | CaCO ₃ - Na ₂ CO ₃ | " | 400 mg | " |
| 11 | DT11 | Pure ³ CaCO ₃ | " | | " |
| | | A/R grade | " | 339 mg | " |
| 12 | DT11A | Pure MgCO ₃ | " | | " |
| | | L/R grade ³ | " | 175 mg | " |
| 13 | DT12 | Calcite | -28 to +35mesh | 400 mg | " |
| 14 | DT13 | " | -20 to +28mesh | " | " |
| 15 | DT14 | " | -14 to +20mesh | " | " |
| 16 | DT15 | " | - 6 to +14mesh | " | " |
| 17 | DT16 | L/S Satna | -90 μ to +63 μ | " | 20°C/min |
| 18 | DT17 | " | " | " | 25°C/min |
| 19 | DT18 | " | " | " | 30°C/min |

3.3.3 Measurement of Carbon di-oxide evolution :-

About 25 gm of sample after drying was kept in the quartz tube which was connected through a mercury pressure regulator to a calibrated capillary flowmeter as shown in fig.(3). The apparatus was first purged by passing CO_2 from cylinder for about 10 minutes. Then the tube was introduced well inside the furnace and CO_2 liberated was measured at regular interval of time. The experimental details of various experiments carried out are given Table III-3.

3.3.4 Temperature measurements in Static bed :-

In another set of experiments, a chromel-alumel thermocouple was placed at the centre of sample (25 gm) and the quartz tube containing the sample was kept well inside the furnace and temperature was measured at regular interval. In some experiments attempts were made to measure the temperature and the rate of liberated CO_2 simultaneously.

3.3.5 Temperature measurements in Moving bed :

A chromel-alumel thermocouple was fixed at a known distance inside the tube containing sample (50 gm) as shown in fig.(4). The mouth of refractory plug in the furnace tube was taken as the reference for measuring distance in all the cases. The tube was pushed inside the furnace slowly at the experiments of 1 cm/min and the temperature was measured at 30 sec. interval. And the details of experimental conditions are given in Table III-4.

T A B L E - III-3

DETAILS OF EXPERIMENTAL CONDITIONS FOR CO₂ EVOLUTIONMEASUREMENTS

| Expt.No. | Material | Amount (gm) | Control Temp. °C | CO ₂ Par- tial Pre- ssure(atm) | Particle size (mesh) | Total Exptl Time(hrs) |
|----------|----------|----------------|---------------------|---|----------------------------|-----------------------------|
| CE0 | Calcite | 31.19 | 1000 | 1.03 | -5 to +14 | 40 |
| CE1 | " | 31.11 | " | " | " | 35 |
| CE2 | " | 27.21 | " | " | " | 25 |
| CE3 | " | 26.92 | " | " | -48 to +65 | 30 |
| CE4 | " | 27.09 | " | " | -14 to +20 | 25 |
| CE5 | " | 27.26 | " | " | +3 | 25 |
| CE6 | L/S-CNB | 28.04 | " | " | -14 to +20 | 20 |
| CE7 | " | 32.23 | " | " | +3 | 20 |
| CE8 | Dolo-CNB | 28.91 | " | " | -14 to +22 | 20 |
| CE9 | Calcite | 27.28 | " | 1.25 | -5 to +14 | 35 |
| CE10 | " | 26.76 | " | " | " | 35 |
| CE11 | " | 26.27 | " | 1.5 | " | 45 |
| CE12 | " | 29.42 | " | 1.5 | " | 45 |
| CE13 | L/S-CNB | 27.33 | " | " | -14 to +20 | 30 |
| CE14 | Calcite | 29.11 | 980 | 1.03 | -5 to +14 | 45 |
| CE15 | " | 29.65 | 980 | " | " | 50 |
| CE16 | " | 29.88 | 950 | " | " | 50 |
| CE17 | " | 32.17 | " | " | " | 60 |
| CE18 | " | 30.96 | " | " | " | 60 |
| CE19 | " | 28.69 | " | 1.03 | -25 to +14 | 60 |
| CE20 | L/S-CNB | 26.59 | " | " | -14 to +20 | 90 |
| CE21 | L/S-CNB | 31.91 | " | " | +3 | 40 |
| CE22 | Dolo-CNB | 26.18 | " | " | -14 to +22 | 40 |
| CE23 | Calcite | 27.43 | " | 1.25 | -5 to +14 | 40 |
| CE24 | L/S-CNB | 27.82 | " | 1.5 | -14 to +20 | 60 |
| CE25 | Calcite | 28.32 | 925 | 1.03 | -5 to +14 | 60 |
| CE26 | " | 25.48 | 900 | 1.03 | -14 to +20 | 60 |
| CE27 | L/S-CNB | 25.55 | " | " | -14 to +20 | 90 |
| CE28 | " | 32.42 | " | " | +3 | 60 |
| CE29 | Dolo-CNB | 29.10 | " | " | -14 to +22 | 30 |
| CE30 | L/S-CNB | 27.37 | " | 1.5 | -14 to +20 | 60 |
| CE31 | " | 28.19 | 850 | 1.03 | " | 20 |
| CE32 | " | 31.22 | " | " | -14 to +22 | 35 |
| CE33 | Dolo-CNB | 28.61 | " | " | " | 30 |
| CE34 | L/S-CNB | 27.82 | " | 1.5 | -14 to +20 | 45 |
| CE35 | Dolo-CNB | 28.76 | 800 | 1.03 | -14 to +22 | 60 |
| CE36 | " | 28.68 | 750 | 1.03 | " | 60 |

T A B L E III-4

EXPERIMENTAL CONDITIONS FOR TEMPERATURE MEASUREMENTSIN STATIC AND MOVING BEDS

Maximum Time = 30min Controller Temperature = 1000°C
 Bed Speed = 1cm/min Sample length-Static = 10 cm
 Sample length-Moving = 20 cm

| Expt. No. | Material | Size(mesh) | Position of Thermocouple | Remarks |
|-----------|------------|------------|--------------------------|------------|
| TM1 | Empty tube | .. | -5 cm | Static bed |
| TM2 | Calcite | -5 to +14 | -5 cm | " |
| TM3 | L/S-CNB | -14 to +20 | " | " |
| TM4 | Dolo-CNB | -14 to +22 | " | " |
| TM5 | Empty tube | .. | 0 | Moving bed |
| TM6 | " | .. | -10 cm | " |
| TM7 | " | .. | -20 cm | " |
| TM8 | " | .. | -27 cm | " |
| TM9 | Calcite | -20 to +28 | 0 | " |
| TM10 | " | " | -5 cm | " |
| TM11 | " | " | -10 cm | " |
| TM12 | " | " | -18 cm | " |
| TM13 | " | " | -22 cm | " |
| TM14 | L/S-CNB | -14 to +22 | 0 | " |
| TM15 | " | " | -5 cm | " |
| TM16 | " | " | -10 cm | " |
| TM17 | " | " | -18 cm | " |
| TM18 | " | " | -22 cm | " |
| TM-CE19 | Calcite | -20 to +28 | -5 cm | Static bed |
| TM-CE20 | L/S-CNB | -14 to +22 | -5 cm | " |

C H A P T E R IV

R E S U L T S

4.1 Results of Derivatograph experiments :-

Results of DTA, TG and DTG experiments i.e. from DT1 to DT18 as obtained from derivatograph are summarized in Table IV-1. The exact plots for some experiments are given in figures from (4) to (13). In samples of dolomite i.e. in experiments DT5 and DT6, weight losses due to calcination of MgCO_3 and CaCO_3 are found separately from the TG plots and these results are marked as 'A' and 'B' respectively in Table IV-1.

4.2 Results of calcite decomposition in Moving bed experiments:-

The results of experiments carried out using moving bed techniques as described in section 3.3.2 for non-isothermal decomposition studies of calcite are given in Table IV-2.

4.3 Results of experiments measuring evolution of Carbon dioxide in Static beds :-

Table IV-3 gives the results of experiments to measure evolution of CO_2 . The details of these experimental conditions such as $p\text{CO}_2$, sample weight, source etc., have been given in Table III-3. Typical plots for the rate of CO_2 evolution for materials like calcite, limestone, and dolomite are given fig.(14). Limestone and dolomite decompose rather easily than calcite. It may be noted that total area under the curve upto certain duration would give total amount of CO_2 liberated in that period and it can be shown that

T A B L E IV-1

RESULTS OBTAINED BY TG PLOTS SHOWING WEIGHT LOSSESAT VARIOUS TEMPERATURES IN DT EXPERIMENTS

| Run No. | Weight loss in mg at Temperature °K | | | | | | Maxm. wt. loss(mg) | Maxm. pct. wt. loss calculate |
|-----------|-------------------------------------|-----|------|------|------|------|--------------------|-------------------------------|
| | 873 | 973 | 1073 | 1173 | 1213 | 1253 | 1273 | |
| DT1 | .. | .. | 4 | 28 | 50 | 100 | 126 | 155 |
| DT2 | .. | 1 | 4 | 30 | 60 | 110 | 156 | 161 |
| DT3 | 1 | 4 | 12 | 44 | 85 | 116 | 136 | 140 |
| DT4 | .. | .. | 2 | 28 | 58 | 108 | 138 | 152 |
| DT5 'A' | .. | 8 | 17 | 86 | .. | .. | .. | 90 |
| DT5 'B' | .. | .. | .. | .. | 78 | 88 | 101 | 102 |
| DT6 'A' | .. | 7 | 14 | .. | .. | .. | .. | 70 |
| DT6 'B' | .. | .. | .. | 30 | 58 | 92 | 102 | 104 |
| DT7 | .. | 2 | 4 | 25 | 52 | 87 | 122 | 126 |
| DT8 | 96 | 104 | 112 | 154 | 188 | 190 | 192 | 192 |
| DT9 | .. | 1 | 2 | 16 | 32 | 48 | 58 | 84 |
| DT10 | .. | .. | 5 | 25 | 35 | 48 | 60 | 125 |
| DT11 | .. | .. | 1 | 74 | 104 | 124 | 144 | 144 |
| DT11A 100 | .. | .. | .. | .. | .. | .. | .. | 100 |
| DT12 | .. | .. | 1 | 13 | 34 | 69 | 104 | 134 |
| DT13 | .. | .. | 4 | 30 | 50 | 110 | 135 | 160 |
| DT14 | .. | .. | 3 | 24 | 36 | 76 | 115 | 159 |
| DT15 | .. | .. | 3 | 20 | 39 | 68 | 97 | 140 |
| DT16 | .. | .. | 1 | 11 | 27 | 73 | 123 | 140 |
| DT17 | .. | .. | 1 | 21 | 49 | 126 | 144 | 162 |
| DT18 | .. | .. | 1 | 20 | 50 | 102 | 154 | 162 |

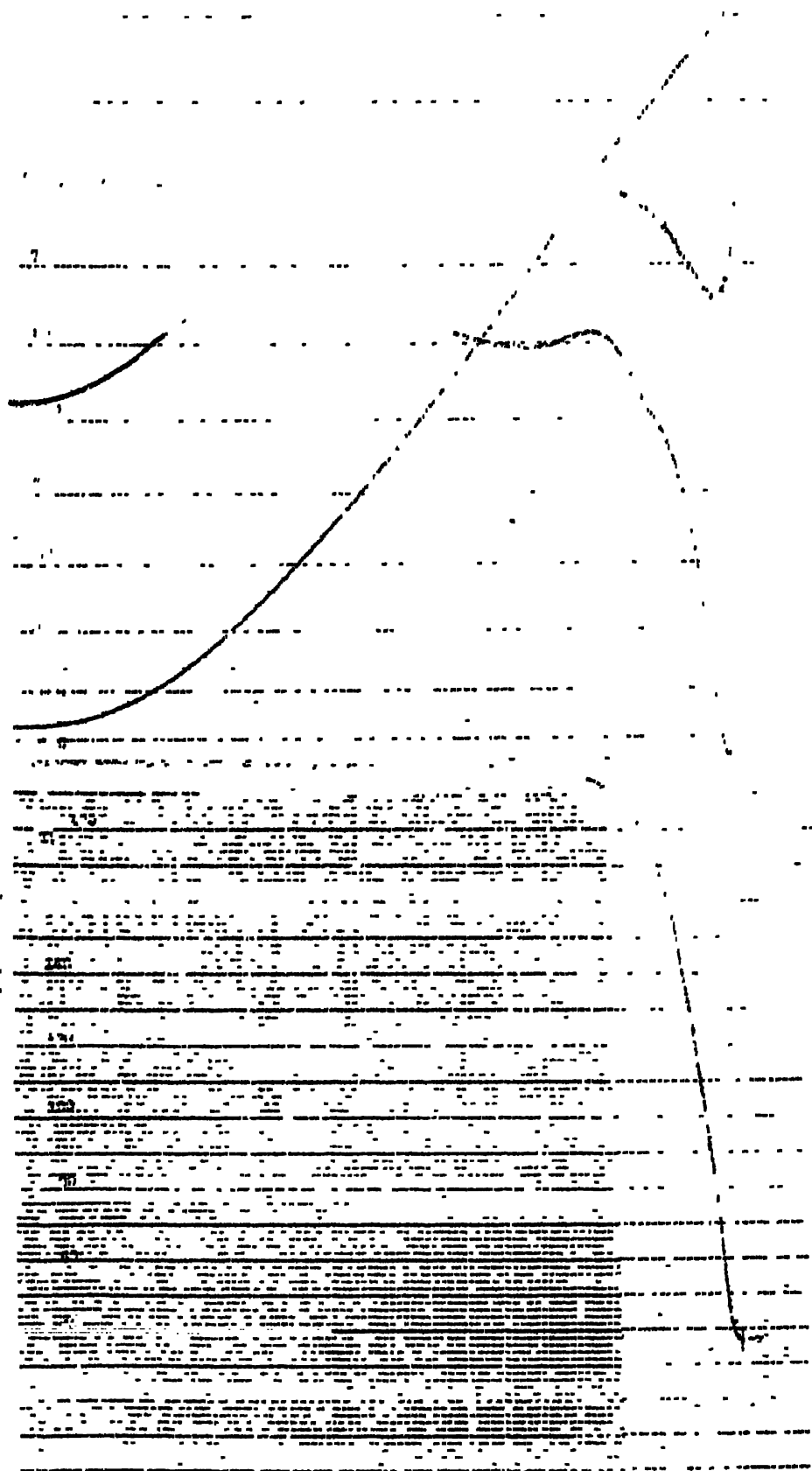


FIG. (4) DTA/TG/DTG/T PLOTS FOR LIMESTONE FROM SATNA

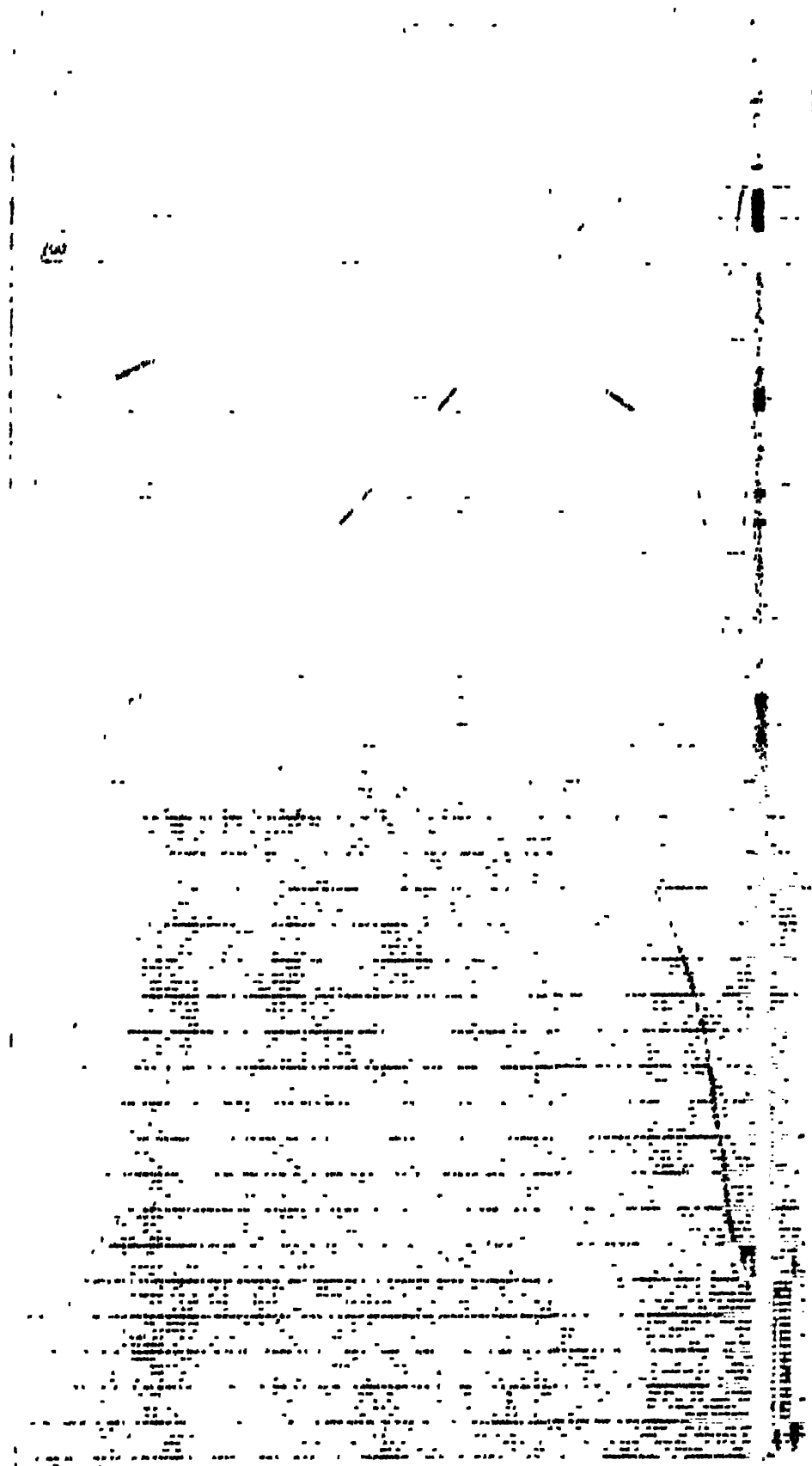


Fig. (5) 3/3/3/T PLOTS FOR LITTONONE REACTOR

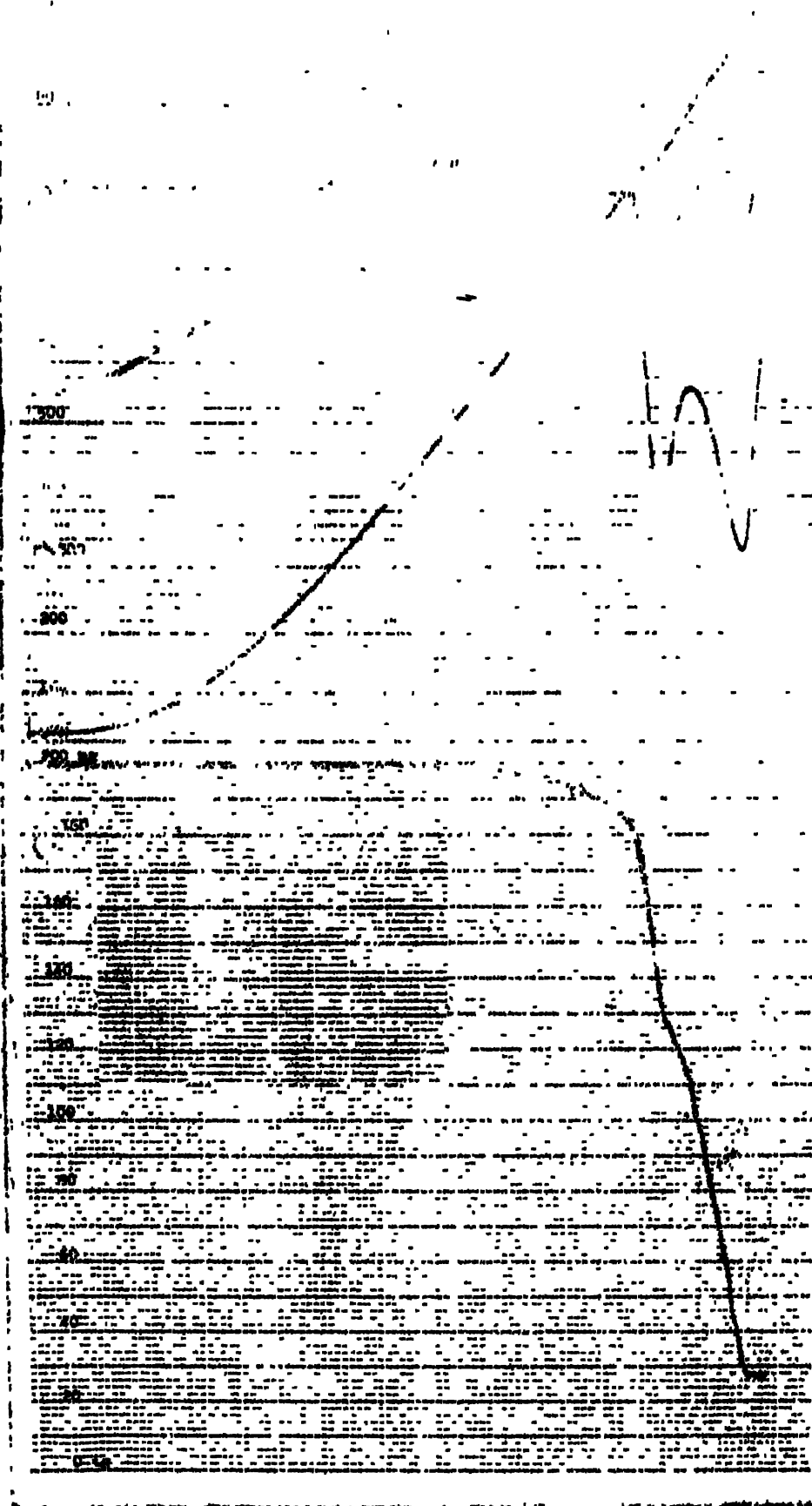


FIG. (6) DTA/TS/DTG/T PLOTS OF DOLOMITE NON REACT

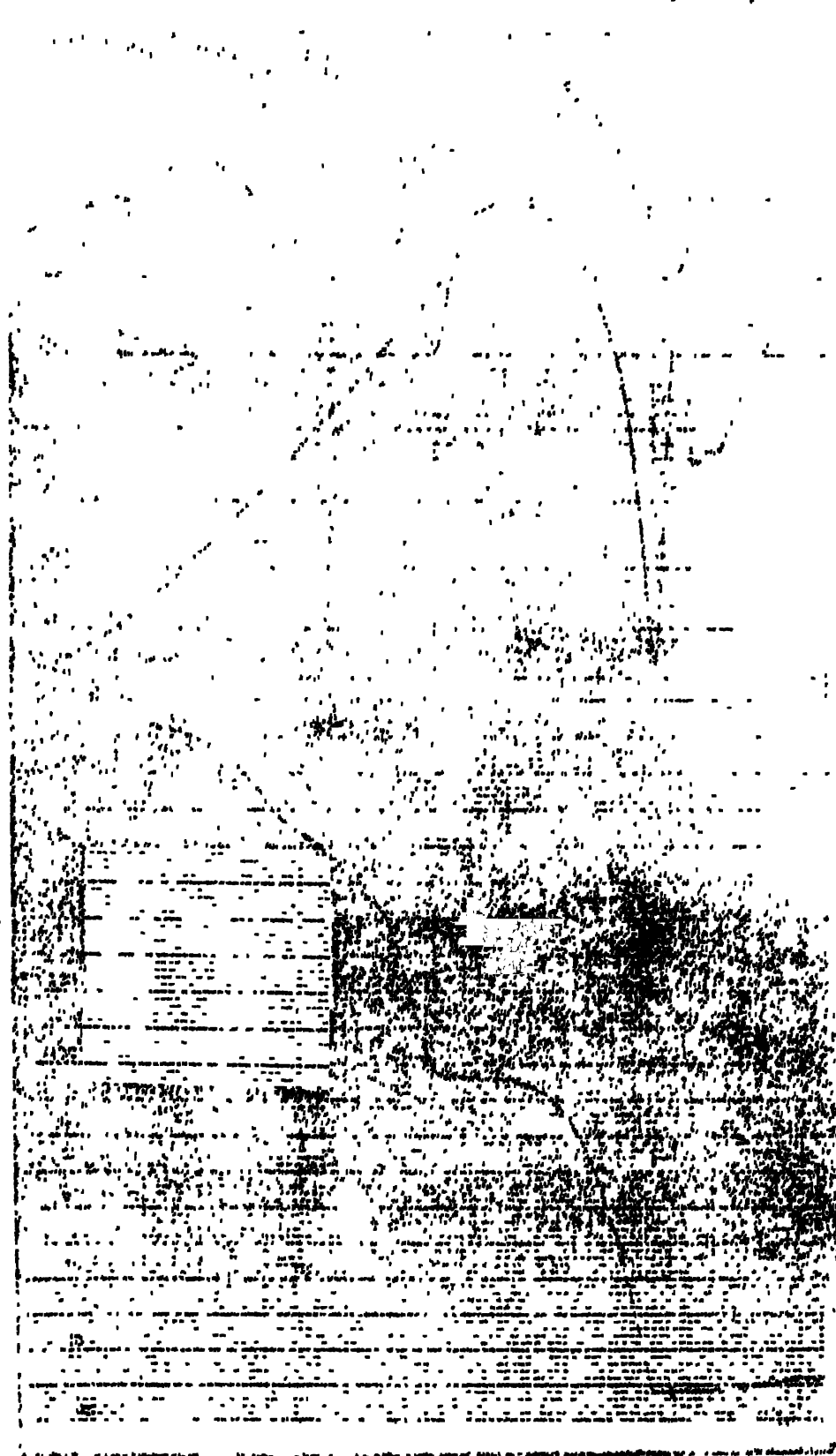


Fig. (8) DTA/TG/DTG/T PLOTS FOR THERMAL ANALYSIS OF
 CaCO_3 AND Na_2CO_3

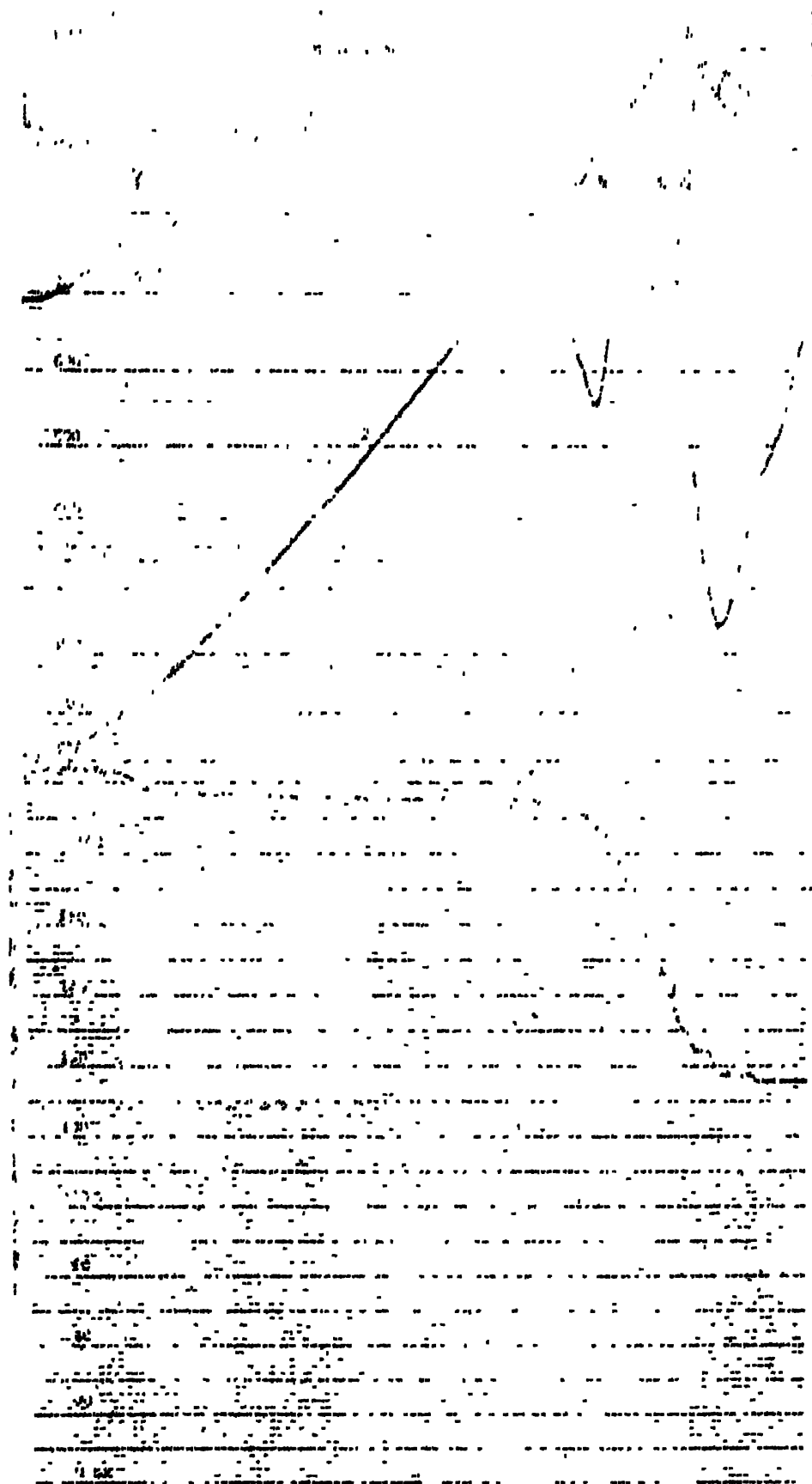
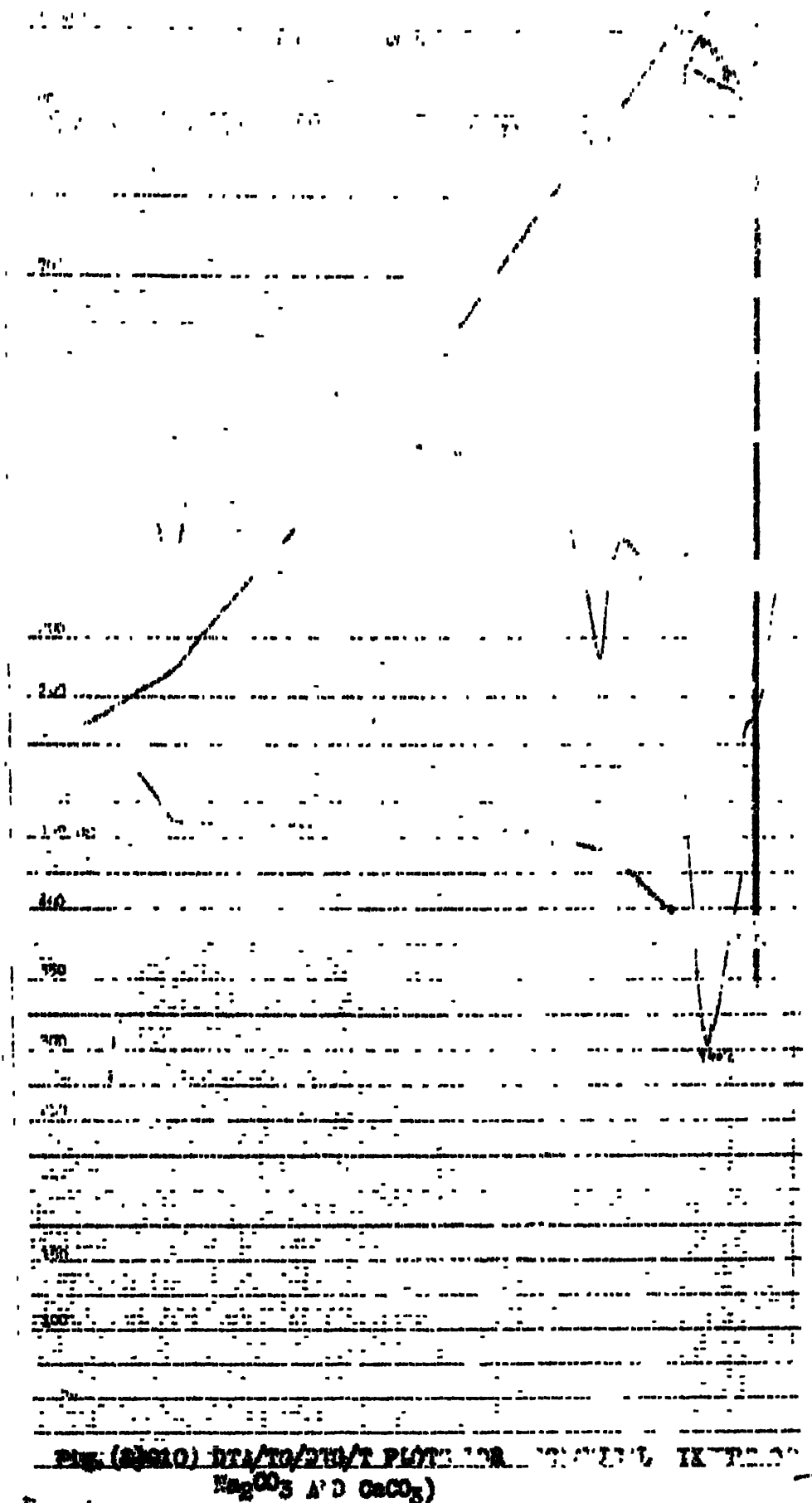
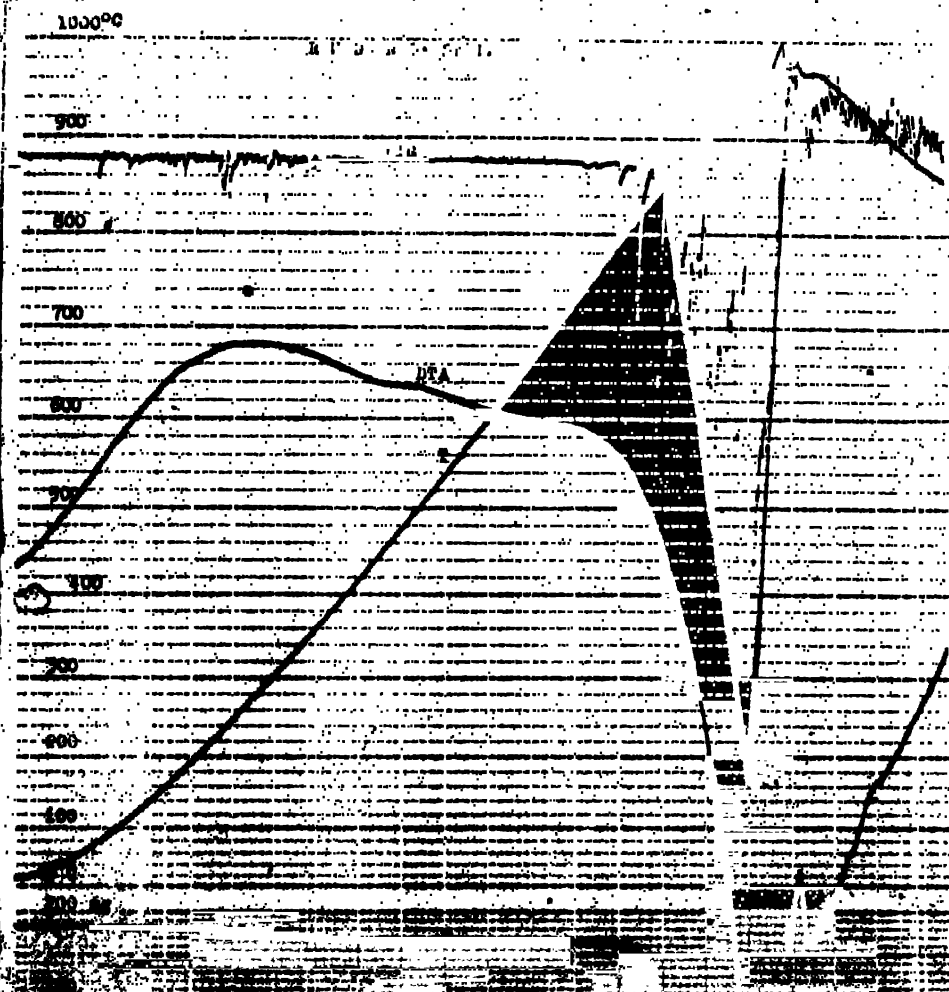


Fig. (3) DTA/TG/DTG/T Plot for Double Carbonate
($\text{Na}_2\text{CO}_3 \cdot \text{CaCO}_3$)





-1000°C

RUN NO. DT 11A

-900

DTG

800

700

600

500

400

300

200

100

0

-100

-200

-300

-400

-500

-600

-700

-800

-900

-1000

DTA

T

②

D

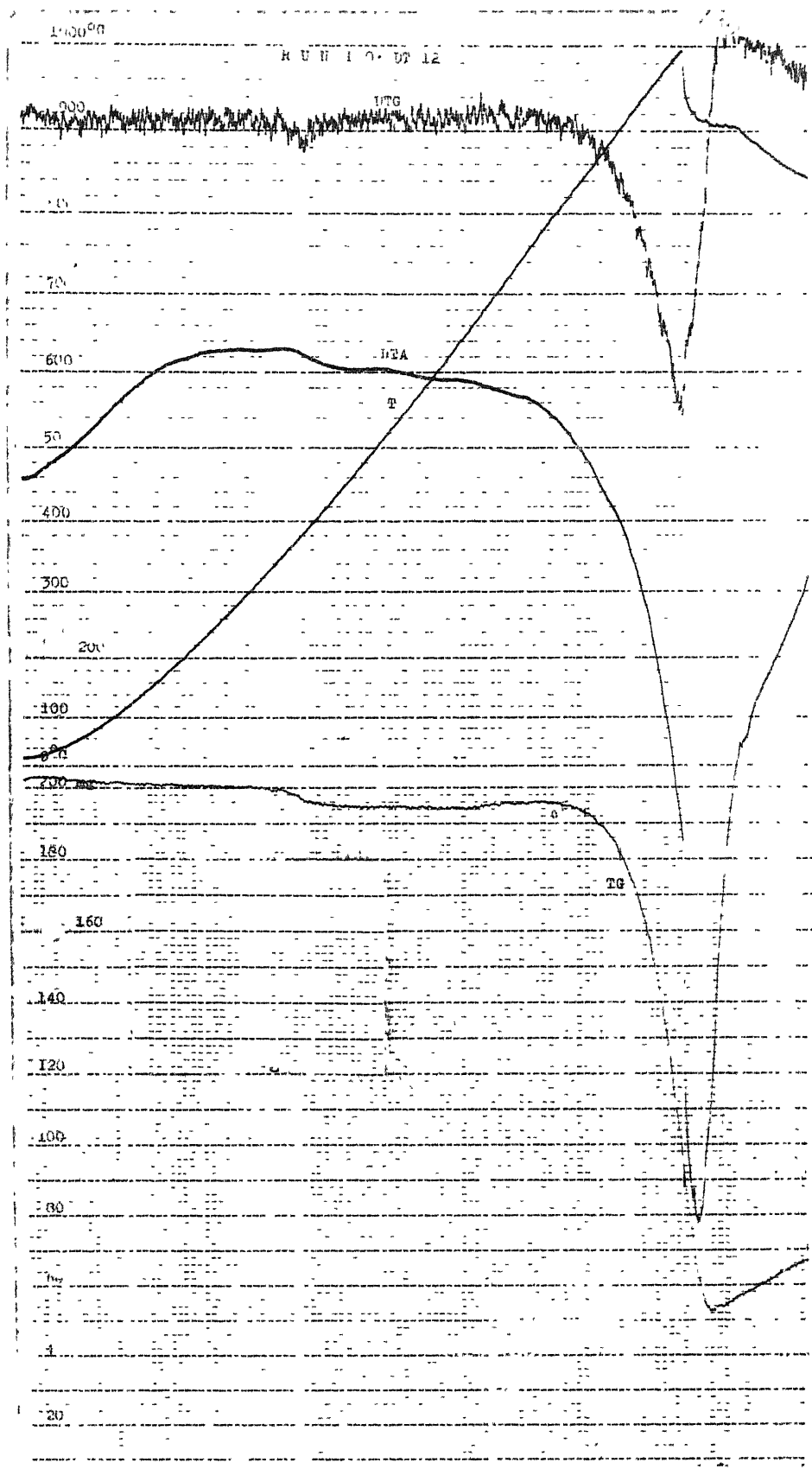


Fig. (13) DTA/TG/DTG/T PLOTS FOR CALCITE

T A B L E IV-2

RESULTS OF CALCITE DECOMPOSITION IN

MOVING BED EXPERIMENTS

| Expt.No. | Maximum Temp. °C | Bed speed cm/min | Pct. loss on ignition of vol. elements collected at distances in cm of | | | | | | | | | |
|----------|---------------------|------------------------|---|-------|-------|--------|-------|-------|-------|-------|--|--|
| | | | 1 - 3 | 3 - 6 | 6 - 9 | 9 - 12 | 12-15 | 15-18 | 18-21 | 21-24 | | |
| MB1 | 911 | 1/2 | 36.61 | 39.39 | 42.99 | 44.56 | .. | .. | .. | .. | | |
| MB2 | 958 | 1/2 | 24.38 | 34.28 | 36.60 | 39.91 | 39.67 | 40.88 | 43.28 | 43.07 | | |
| MB3 | 1015 | 1/2 | 8.57 | 8.97 | 9.20 | 16.12 | 25.32 | 35.36 | 39.92 | 42.76 | | |
| MB4 | 911 | 1 | 39.38 | 42.62 | 41.31 | .. | .. | .. | .. | .. | | |
| MB5 | 958 | 1 | 33.13 | 38.49 | 40.17 | 42.31 | 43.06 | 41.70 | .. | .. | | |
| MB6 | 1015 | 1 | 12.83 | 13.56 | 22.41 | 29.62 | 33.31 | 37.78 | 40.65 | 42.28 | | |

T A B L E IV-3

SUMMARY OF RESULTS OBTAINED FROM CO₂ EVOLUTION EXPERIMENTS

| Expt. No. | Measured Temp. °C | Actual wt. loss (gm) | | Cumulative calculated wt. loss (gm) | | | | | | Measured loss (gm) | Calculated loss |
|-----------|-------------------|----------------------|-----------|-------------------------------------|-------|-------|-------|-------|-------|--------------------|-----------------|
| | | wt. loss (gm) | pct. loss | 5 min | 10min | 15min | 20min | 25min | 30min | | |
| CE0 | 1002 | 13.36 | 42.84 | 2.41 | 6.78 | 10.18 | 16.33 | 17.83 | 14.74 | 15.54 | 49.87 |
| CE1 | 1005 | 11.48 | 42.17 | 4.09 | 8.24 | 9.65 | 11.12 | 12.06 | .. | 12.06 | 44.32 |
| CE2 | 995 | 10.57 | 39.25 | 3.55 | 6.72 | 8.06 | 8.87 | 9.41 | 9.57 | 9.57 | 35.55 |
| CE3 | 1015 | 11.40 | 42.06 | 2.74 | 6.56 | 8.01 | 9.68 | 10.43 | 10.75 | 10.75 | 39.68 |
| CE4 | 1015 | 11.64 | 42.71 | 3.92 | 8.82 | 11.45 | 12.25 | 12.41 | .. | 12.41 | 45.52 |
| CE5 | 1015 | 12.06 | 43.00 | 7.50 | 10.99 | 13.00 | 13.27 | .. | .. | 13.27 | 47.33 |
| CE6 | 1004 | 14.13 | 43.83 | 5.90 | 10.99 | 13.13 | 13.67 | .. | .. | 13.67 | 42.41 |
| CE7 | 1009 | 13.42 | 46.43 | 11.37 | 15.23 | 16.30 | 16.41 | .. | .. | 16.41 | 56.76 |
| CE8 | 996 | 11.28 | 41.35 | 2.48 | 5.90 | 8.58 | 10.39 | 11.73 | 12.66 | 13.27 | 48.64 |
| CE9 | 1010 | 11.14 | 41.53 | 2.08 | 5.63 | 8.71 | 11.06 | 12.80 | 14.20 | 15.21 | 56.84 |
| CE10 | 1015 | 10.75 | 40.89 | 1.41 | 4.36 | 6.57 | 8.04 | 9.11 | 9.65 | 12.13 | 46.17 |
| CE11 | 1008 | 12.24 | 41.61 | 1.94 | 5.16 | 7.64 | 9.31 | 10.45 | 11.19 | 11.73 | 39.87 |
| CE12 | 1008 | 11.92 | 43.62 | 3.55 | 7.17 | 8.98 | 9.78 | 10.18 | 10.32 | 10.32 | 37.76 |
| CE13 | 980 | 12.37 | 42.47 | 1.34 | 4.02 | 6.43 | 8.58 | 10.18 | 11.66 | 14.07 | 48.33 |
| CE14 | 978 | 12.38 | 41.75 | 1.54 | 4.96 | 7.44 | 10.5 | 11.79 | 12.80 | 15.08 | 50.86 |
| CE15 | 945 | 11.66 | 39.04 | 1.21 | 2.95 | 4.29 | 5.63 | 6.30 | 6.83 | 11.52 | 38.55 |
| CE16 | 943 | 10.08 | 31.35 | 1.21 | 2.95 | 4.82 | 6.70 | 8.31 | 9.65 | 15.87 | 41.33 |
| CE17 | 940 | 12.75 | 41.17 | 0.94 | 2.81 | 4.56 | 6.16 | 7.77 | 9.11 | 16.08 | 51.50 |
| CE18 | 950 | 9.67 | 33.69 | 0.54 | 1.74 | 3.42 | 5.23 | 6.37 | 7.24 | 9.65 | 33.63 |
| CE19 | 959 | 11.34 | 42.63 | 2.14 | 4.76 | 6.83 | 7.97 | 8.71 | 9.38 | 9.92 | 37.31 |
| CE20 | 955 | 13.85 | 43.33 | 2.95 | 6.43 | 99.38 | 11.52 | 13.13 | 13.50 | 13.80 | 43.25 |
| CE21 | 959 | 12.72 | 45.88 | 5.15 | 9.01 | 11.05 | 12.44 | 13.41 | 13.94 | 14.53 | 55.50 |
| CE22 | 958 | 9.40 | 34.27 | .. | .. | .. | .. | .. | .. | 14.07 | 51.29 |
| CE23 | 953 | 11.31 | 40.67 | 2.28 | 4.02 | 5.70 | 6.90 | 7.77 | 8.51 | 10.45 | 37.56 |
| CE24 | 923 | 6.41 | 22.40 | 0.97 | 2.68 | 4.29 | 5.15 | 5.42 | 5.57 | 5.57 | 19.67 |
| CE25 | 901 | 0.29 | 1.21 | .. | .. | .. | .. | .. | .. | 0.28 | 1.09 |
| CE26 | 908 | 5.13 | 20.06 | 2.01 | 2.35 | 2.41 | 2.48 | 2.55 | 2.61 | 3.42 | 13.39 |
| CE27 | 904 | 5.49 | 16.93 | 1.88 | 2.14 | 2.41 | 2.68 | 2.95 | 3.22 | 4.55 | 14.03 |
| CE28 | 901 | 6.78 | 23.20 | 3.10 | 6.22 | 6.76 | 6.92 | 7.24 | 7.56 | 7.56 | 25.98 |
| CE29 | 901 | 2.95 | 10.79 | 2.01 | 2.81 | 2.95 | 3.02 | 3.08 | 3.15 | 3.55 | 12.97 |
| CE30 | 901 | 2.95 | 10.79 | 2.01 | 2.81 | 2.95 | 3.02 | 3.08 | 3.15 | 3.55 | 12.97 |

T A B L E IV-3

SUMMARY OF RESULTS OBTAINED FROM CO₂ EVOLUTION EXPERIMENTS

| Expt. No. | Measured Temp. °C | Actual wt. loss (gm) | Actual loss pct. | Cumulative calculated wt. loss (gm) | | | | | Measured loss (gm) | | Calculated loss pct. |
|--------------|----------------------|----------------------------|---------------------|-------------------------------------|--------|--------|--------|--------|--------------------|--------|----------------------|
| | | | | 5 min | 10 min | 15 min | 20 min | 25 min | 30 min | red lo | ted pct. |
| | | | | | | | | | | miss | loss |
| CE31 | 843 | 2.77 | 9.83 | 1.41 | 2.21 | 2.31 | 2.38 | 2.95 | 3.22 | 2.38 | 8.44 |
| CE32 | 850 | 3.33 | 10.66 | 1.47 | 2.14 | 2.41 | 2.68 | 2.95 | 3.22 | 3.35 | 10.73 |
| CE33 | 849 | 6.41 | 22.40 | 0.97 | 2.68 | 4.29 | 5.15 | 5.42 | 5.57 | 5.57 | 19.47 |
| CE34 | 841 | 2.78 | 10.00 | 1.61 | 2.61 | 2.68 | 2.71 | 2.75 | 2.78 | 2.88 | 10.35 |
| CE35 | 787 | 6.30 | 21.89 | 0.15 | 1.09 | 2.21 | 3.25 | 4.06 | 4.73 | 6.33 | 22.01 |
| CE36 | 741 | 1.47 | 5.11 | 0.01 | 0.06 | 0.11 | 0.20 | 0.29 | 0.42 | 1.52 | 5.50 |

CE 21
L/S
CMB
955°C

CE 22
DOLOMITE - CMB
959°C

FIG. (1.1) TYPICAL PLOTS (CO_2 EVOLUTION) OF CC/SEC AGAINST TIME FOR CALCITE, L/S, DOLOMITE.

CE 19
CALCITE 950°C

period and it can be thus related to the loss in weight of the sample as shown in fig.(15). This has been verified and confirmed by actual weighing of the sample at the end of experiments.

In those cases where the patching is not very good error is presumably in the measurement of CO_2 evolved especially in the initial stages or due to improper calibration of the flow-meter. The initial rate of evolution in some cases especially with limestone and dolomite was very large could not be determined accurately. Weight loss data for such experiments are suitably corrected by simple additions, subtractions or by multiplications by comparing the actual weight loss of sample with measured weight loss from CO_2 evolution plot at the end of experiments. The corrected data are summarized in Table IV-4.

4.4 Temperature measurements on heating of Static bed (Results):-

Fig.(16) shows the results of temperature measurements of calcite, limestone and dolomite in static beds contained in tubes. For comparison purposes, temperature response of the thermocouple in empty tube is also plotted in the fig.(16). The results of the simultaneous measurement of temperature and CO_2 evolution are given in fig.(17).

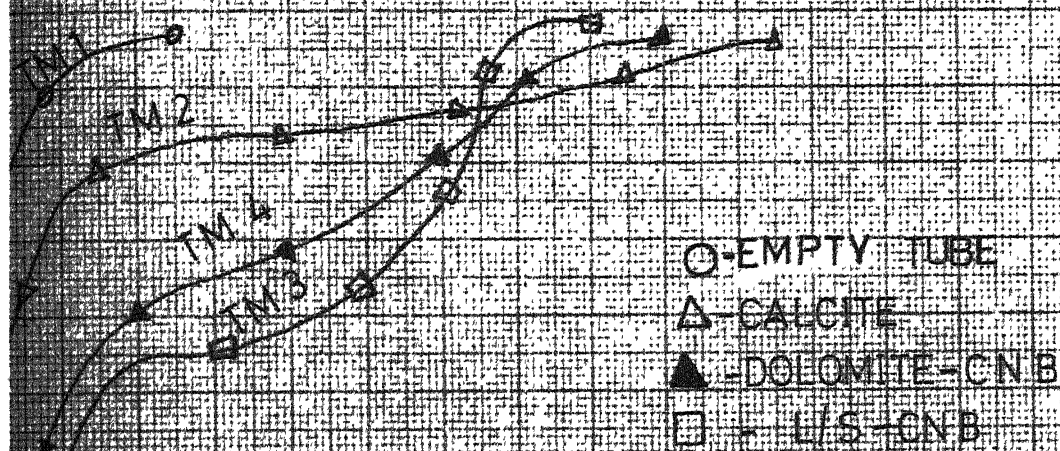
4.5 Results of measurement of temperature during Moving bed experiments :-

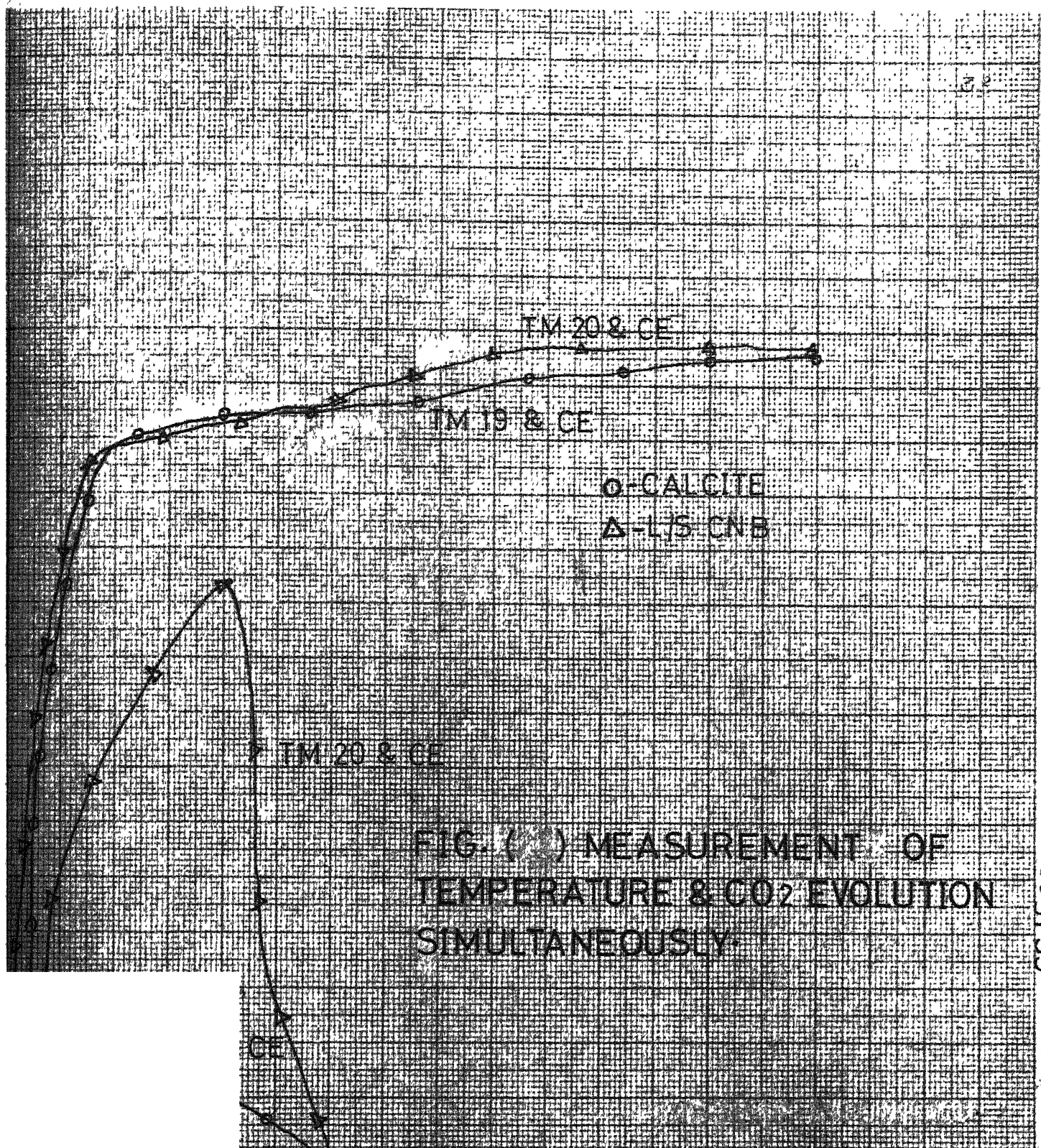
A number of experiments were carried out to understand the variation of temperature with time to different volume elements in a moving bed when the tube was introduced into the furnace under a given set of conditions. The results of temperature measurements in empty tube, for calcite and limestone (TM5 to TM18) of Table III-4 are described in figures (18), (19) and (20).

T A B L E IV-4

CORRECTED WEIGHT LOSS RESULTS ON CO₂ EVOLUTION EXPERIMENTS

| Expt. No. | Weight loss at various time in gm | | | | | | |
|-----------|-----------------------------------|-------|-------|-------|-------|-------|--|
| | 5 min | 10min | 15min | 20min | 25min | 30min | |
| CE0 | 0.23 | 4.52 | 8.00 | 10.15 | 11.65 | 12.65 | |
| CE1 | 1.69 | 5.25 | 7.93 | 10.77 | 11.41 | 12.41 | |
| CE2 | 3.51 | 7.66 | 9.07 | 10.54 | 11.48 | .. | |
| CE3 | 4.55 | 7.72 | 9.06 | 9.87 | 10.41 | 10.57 | |
| CE4 | 3.39 | 7.21 | 8.66 | 10.33 | 11.08 | 11.40 | |
| CE5 | 3.15 | 8.05 | 10.68 | 11.48 | 11.64 | .. | |
| CE6 | 6.29 | 9.78 | 11.79 | 12.06 | .. | .. | |
| CE7 | 6.36 | 11.45 | 13.59 | 14.13 | .. | .. | |
| CE8 | 8.38 | 12.24 | 13.31 | 13.42 | .. | .. | |
| CE9 | .49 | 3.91 | 6.59 | 8.40 | 9.74 | 10.67 | |
| CE11 | 0.03 | 2.98 | 5.19 | 6.66 | 7.73 | 8.23 | |
| CE12 | 2.45 | 5.67 | 8.15 | 9.82 | 10.96 | 11.70 | |
| CE13 | 5.15 | 8.77 | 10.58 | 11.38 | 11.73 | 11.92 | |
| CE14 | 0.02 | 2.70 | 5.11 | 7.26 | 8.86 | 10.34 | |
| CE15 | .. | 2.26 | 4.74 | 7.75 | 9.09 | 10.10 | |
| CE19 | 0.56 | 1.76 | 3.44 | 5.25 | 6.39 | 7.26 | |
| CE20 | 3.56 | 6.18 | 8.25 | 9.39 | 10.13 | 10.80 | |
| CE21 | 2.98 | 6.46 | 9.43 | 11.55 | 13.16 | 13.53 | |
| CE22 | 3.34 | 7.20 | 9.24 | 10.63 | 11.60 | 12.13 | |
| CE24 | 3.14 | 4.88 | 6.56 | 7.76 | 8.63 | 9.37 | |
| CE25 | 1.07 | 1.34 | 1.67 | 1.98 | 2.24 | 2.48 | |
| CE28 | 2.82 | 3.08 | 3.35 | 3.62 | 3.89 | 4.14 | |
| CE29 | 2.22 | 5.44 | 5.98 | 6.14 | 6.46 | 6.78 | |
| CE30 | 1.41 | 2.21 | 2.35 | 2.42 | 2.48 | 2.55 | |
| CE31 | 1.80 | 2.60 | 2.70 | 2.77 | .. | .. | |
| CE32 | 1.45 | 2.12 | 2.39 | 2.66 | 2.93 | 3.20 | |
| CE33 | 1.81 | 3.52 | 5.13 | 5.99 | 6.26 | 6.41 | |
| CE34 | 1.51 | 2.51 | 2.58 | 2.61 | 2.65 | 2.68 | |
| CE35 | 0.13 | 1.06 | 2.18 | 3.22 | 4.03 | 4.70 | |
| CE36 | .. | 0.01 | 0.06 | 0.15 | 0.24 | 0.37 | |





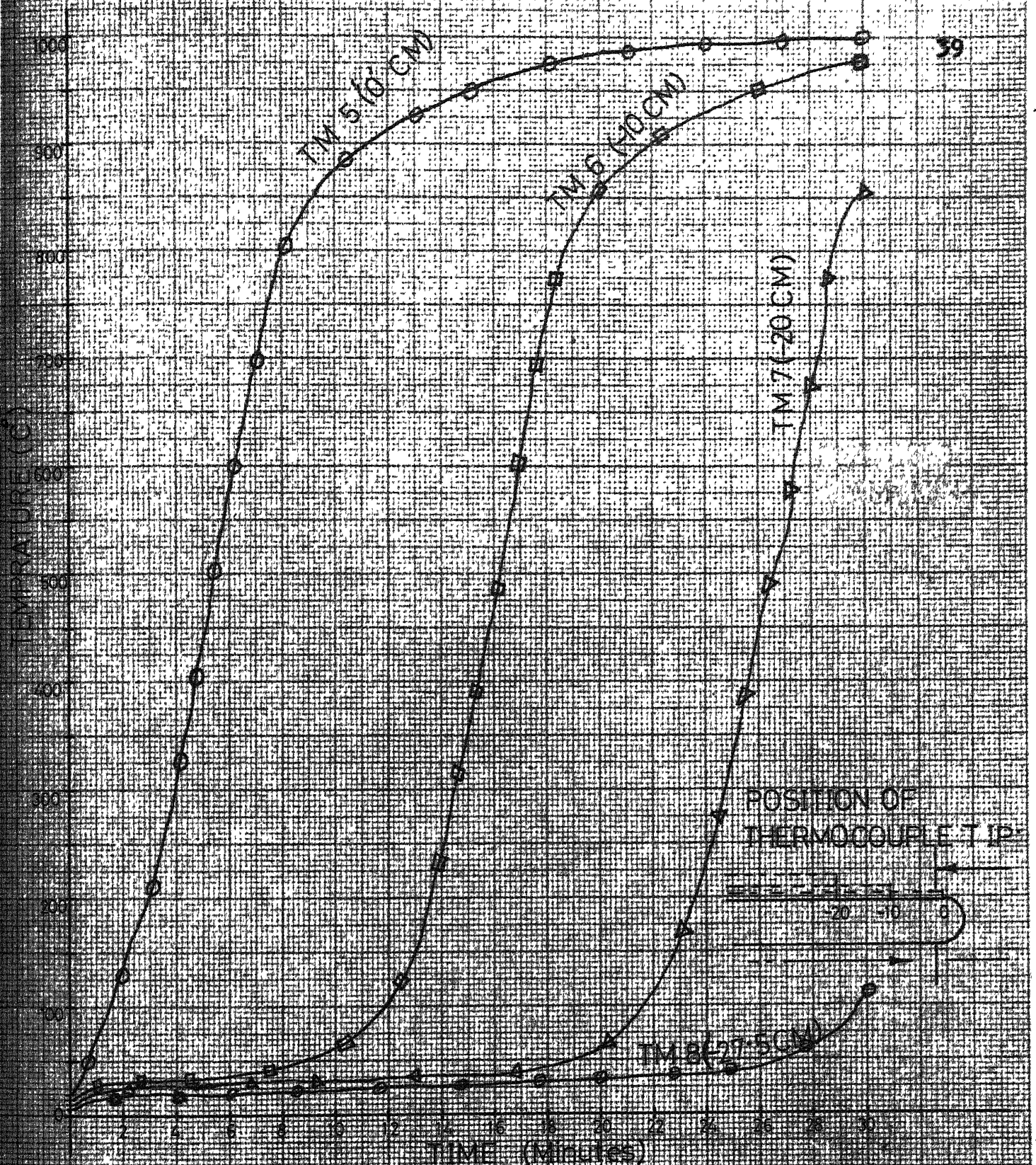


FIG () TEMPERATURE MEASUREMENTS IN A MOVING
 EMPTY TUBE
 BED SPEED = 1 CM/MIN

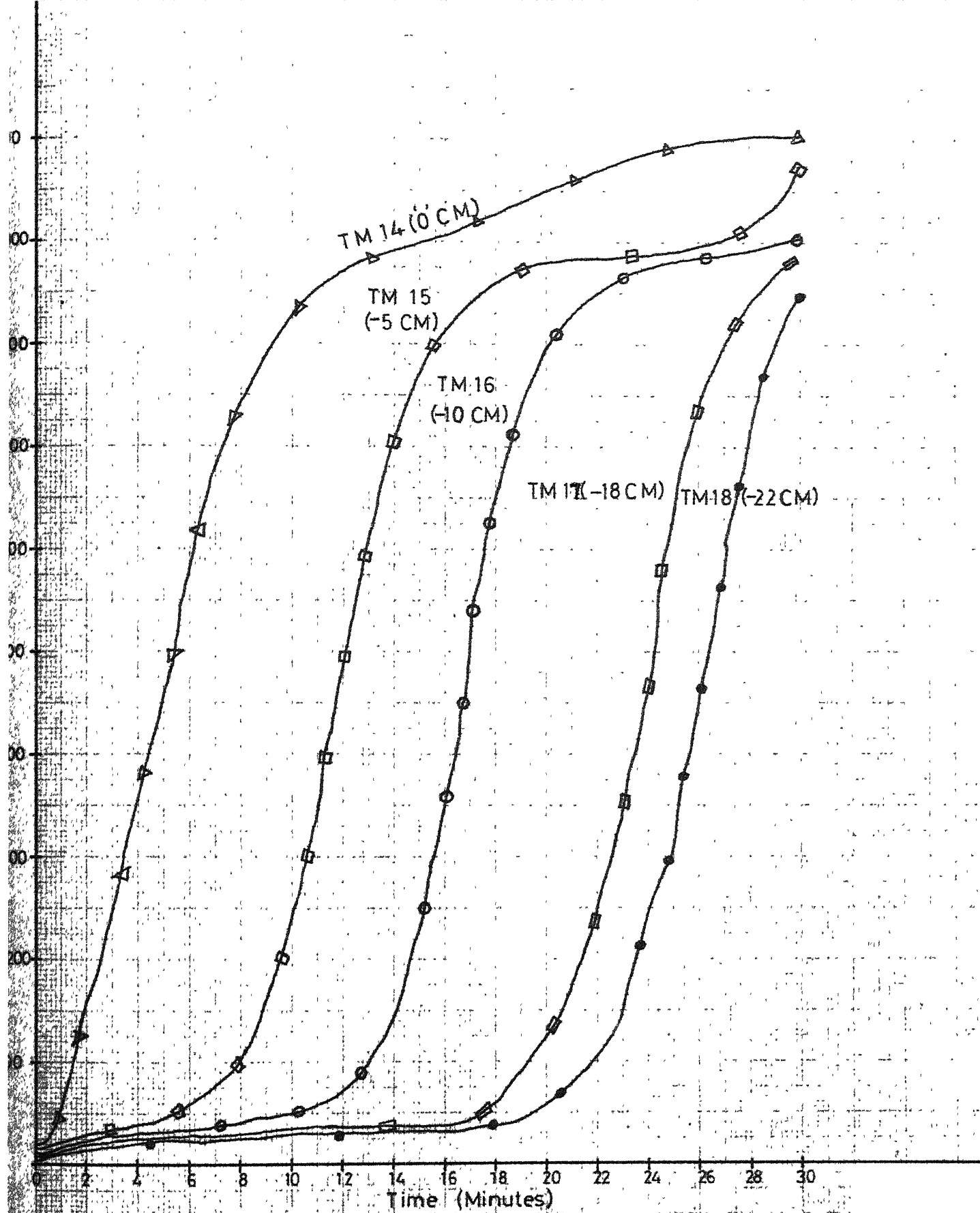


FIG. (20) TIME TEMPERATUR PLOTS
FOR L/S IN MOVING BED.

1) SPEED = 1 CM/Min)

C H A P T E R V

D I S C U S S I O N

5.1 DTA Experiments :-5.1.1 Standardization of experimental conditions for Thermal Analysis :

It is well known that thermo-analytical data are generally dependent on experimental conditions. These conditions include amount of sample weight, particle size, rate of heating, flow rate of gas, nature of packing etc. In the present work, the following standard conditions were maintained unless otherwise mentioned,

| | | |
|---------------------|---|---|
| Weight of sample | = | 400 mg |
| Particle size range | = | -90 μ to +63 μ (75 μ) |
| Heating rate | = | 25°C/min |
| Inert gas flow rate | = | 1 cc/min |
| Nature of packing | = | 5 taps on the crucible as standardized by the operator. |

In many runs, particularly with calcite, calcination was not complete fig.(13) even when the maximum temperature of 1000°C was reached. Some further calcination occurred during cooling of the furnace and it stopped when temperature fell below the decomposition temperature of CaCO_3 . In such cases, the maximum loss in weight of the sample is found to be less than the theoretical value of 44 pct. for pure CaCO_3 decomposition. In other samples from mines presence of impurities such as SiO_2 , Al_2O_3 and Fe_2O_3 in the sample may lead to lower values of percentage loss in weight than the theoretical values.

5.1.2 Dissociation of Carbonate mixtures:

When two carbonates are present together decomposition reactions ^{*}may or may not overlap. The exact decomposition behaviour will depend strongly on the nature of association of the carbonates. For example if the two carbonates are in the form of a mechanical mixture then each decomposition reaction represents decomposition of a pure substance. If however, these carbonates exist in the nature of a compound then the dissociation behaviour is more complex.

For example data in figures (11) and (12) for pure MgCO_3 and for pure CaCO_3 show that decomposition of MgCO_3 occurs at temperature about 500°C , that of CaCO_3 occurs at 900°C . A mechanical mixture of MgCO_3 and CaCO_3 for which data is given in fig.(8) shows two separate DTA peaks and TG plots as expected one corresponding to MgCO_3 at 600°C and another corresponding to CaCO_3 at about 900°C . On the other hand dolomite is a compound of MgCO_3 and CaCO_3 and its decomposition is delayed due to its decreased activity in the compound DTA data in fig.(6) show that decomposition starts at temperature of 800°C which is much above the decomposition temperature of MgCO_3 . However once MgCO_3 has dissociated the CaCO_3 is no longer locked up in dolomite. Therefore the dissociation behaviour of CaCO_3 in dolomite will be same as in pure limestone.

Figures (9) and (10) show experimental data in another interesting system i.e. $\text{Na}_2\text{CO}_3 \cdot \text{CaCO}_3$. If a mechanical mixture ^{*}must occur in sequence. These sequential reactions

←

of sodium carbonate (Na_2CO_3) and CaCO_3 is heated there is no weight loss due to decomposition of Na_2CO_3 because it is thermodynamically stable upto 1200°C even after melting at temperature of 850°C . The thermal analysis data shows an endothermic peak occur around 870°C without any significant loss in weight. This peak therefore must ascribed to melting of Na_2CO_3 . Decomposition of CaCO_3 in the mixture is delayed as it might have reacted with molten Na_2CO_3 to form a double compound $\text{Na}_2\text{CO}_3 \cdot \text{CaCO}_3$. Thermal analysis data for mechanical mixture of Na_2CO_3 and CaCO_3 and the compound $\text{Na}_2\text{CO}_3 \cdot \text{CaCO}_3$ are therefore comparable.

5.1.3 Dissociation behaviour of samples from Mines :-

In samples of limestone and dolomite collected from the various mines, some decomposition occurred at temperatures lower than 900°C , which can be due to presence of MgCO_3 . This is clear from DTA and TG plots in figures (4) and (5), of runs DT1 to DT7 where results are summarized in Table IV-1. Results of DT5'A' and DT6'A' in Table IV-1 corresponds to decomposition of MgCO_3 in dolomite while DT5'B' and DT6'B' correspond to decomposition of CaCO_3 in the dolomite.

Dolomite sample from Chopan does not show any decomposition at temperature less than 900°C , as there is no corresponding peak for MgCO_3 in fig.(7). It is thus basically limestone. This demonstrates the utility of thermal analysis in identifying mineral constituents of ore sample.

5.2 Determination of Activation Energy from TG data :-

5.2.1 α - T plots :

Some of the TG data (weight loss) shown in Table IV-1 have been used to obtain α -T plots for dissociation of various samples. Here ' α ' denotes the fraction decomposed at any temperature $T^{\circ}\text{K}$ and is obtained as follows,

$$\alpha = \frac{\text{Actual weight loss}}{\text{Maxm. wt. loss corresponding to complete decomposition}} \quad \text{---(4)}$$

The value of α for these runs (DT1 to DT4 and DT12 to DT15) are summarized in Table V-1.

5.2.2 Analysis of non-isothermal data:

The basic equation of non-isothermal kinetic is obtained by combining three equations:

$$1. \text{ Kinetic law, } \frac{d\alpha}{dt} = kf(\alpha) \quad \text{-----(5)}$$

$$2. \text{ Arrhenius type equation, } k = A \exp(-E/RT) \quad \text{-----(6)}$$

$$3. \text{ Temperature-Time equation, } T = f(t) \quad \text{-----(7)}$$

$$\text{For constant heating rate } \frac{dT}{dt} = B \quad \text{-----(8)}$$

$$\frac{d\alpha}{f(\alpha)} = \frac{A \exp(-E/RT) dT}{B} \quad \text{--(9)}$$

$$\text{Integrating, } \int_0^{\alpha} \frac{d\alpha}{f(\alpha)} = g(\alpha) = \int_{\frac{A}{B}}^T \exp(-E/RT) dT \quad \text{--(10)}$$

Here ' α ' denotes the degree of reaction (fraction decomposed) at time ' t ', ' A ' and ' E ' are kinetic parameters which satisfy an Arrhenius type equation. ' R ' is the gas constant and ' B ' is the heating rate (constant), $g(\alpha)$ and $f(\alpha)$ are function whose form is determined by the reaction mechanism. There are many

T A B L E V-1

CALCULATIONS OF FRACTION DECOMPOSED(α) VERSUS
TEMPERATURE FROM TG PLOTS OF DT EXPERIMENTS

| Run No. | α at various Temperatures °K | | | | | |
|---------|-------------------------------------|------|------|------|------|------|
| | 1073 | 1113 | 1173 | 1213 | 1253 | 1273 |
| DT1 | 0.03 | 0.08 | 0.18 | 0.32 | 0.65 | 0.81 |
| DT2 | 0.03 | 0.05 | 0.19 | 0.37 | 0.68 | 0.97 |
| DT3 | 0.09 | 0.14 | 0.31 | 0.61 | 0.83 | 0.97 |
| DT4 | 0.01 | 0.04 | 0.18 | 0.38 | 0.71 | 0.91 |
| DT12 | 0.01 | 0.02 | 0.07 | 0.19 | 0.39 | 0.59 |
| DT13 | 0.02 | 0.06 | 0.17 | 0.28 | 0.63 | 0.77 |
| DT14 | 0.02 | 0.06 | 0.14 | 0.20 | 0.43 | 0.65 |
| DT15 | 0.02 | 0.03 | 0.11 | 0.15 | 0.39 | 0.55 |

methods of solving this equation all of which are approximate in nature. The most popular solution used frequently in the literature has been given by Coats and Redfern [11]. According to them if,

$$g(\alpha) = 1 - (1 - \alpha)^{1/3} = kt \quad \text{..(11)}$$

$$\text{and } f(\alpha) = 3(1 - \alpha)^{2/3} \quad \text{.....(12)}$$

$$\text{then, } \frac{1 - (1 - \alpha)^{1/3}}{T^2} = \frac{AR}{3BE} [1 - 2RT/E] \exp[-E/T^2] \quad \text{..(13)}$$

The value of activation energy is obtained by plotting $\ln[1 - (1 - \alpha)^{1/3}]/T^2$ versus $1/T$ for the case of $2RT/E \ll 1$.

Another method of calculating 'E' from non-isothermal kinetic data has been given by Ingraham [12] according to whom,

$$\ln[B\alpha/T^3] = E/RT \quad \text{.....(14)}$$

Activation energy 'E' in this case can be obtained by plotting $\ln[B\alpha/T^3]$ versus $1/T$. The calculated 'E' values using method of least squares for the above mentioned equations are summarized in Table V-2. Actual plots for the two equations for typical limestone and calcite materials are shown in fig. (28).

Activation energy values of around 39 Kcal/mole obtained in Table V-2 are comparable to the reported value of 40.5 Kcal/mole [13] for single crystal study of calcite in vacuum.

5.3 Temperature Measurement and α -t(time) plots obtained from Moving bed experiments:-

Fig.(21) shows the α -t plots for some moving bed experiments described earlier. α values were obtained from the analysis (pct. LOI) of volume elements of the bed as stated in Table IV-2 as following,

T A B L E V-2

CALCULATION OF ACTIVATION ENERGY FROM TG DATA IN
DT EXPERIMENTS

| Run No. | Coats + Redfern | | Ingraham | |
|---------|-----------------|----------------------|----------|----------------------|
| | Slope | 'E' in Kcal /mole | Slope | 'E' in Kcal /mole |
| DT1 | +18680 | -37.36 | -18958 | -37.92 |
| DT2 | +18995 | -37.99 | -19074 | -38.15 |
| DT3 | +19138 | -38.28 | -19137 | -38.27 |
| DT4 | +19086 | -38.17 | -19220 | -38.44 |
| DT12 | +19043 | -38.09 | -19354 | -38.71 |
| DT13 | +18965 | -37.93 | -19424 | -38.85 |
| DT14 | +18875 | -37.75 | -19507 | -39.01 |
| DT15 | +18797 | -37.59 | -19595 | -39.19 |

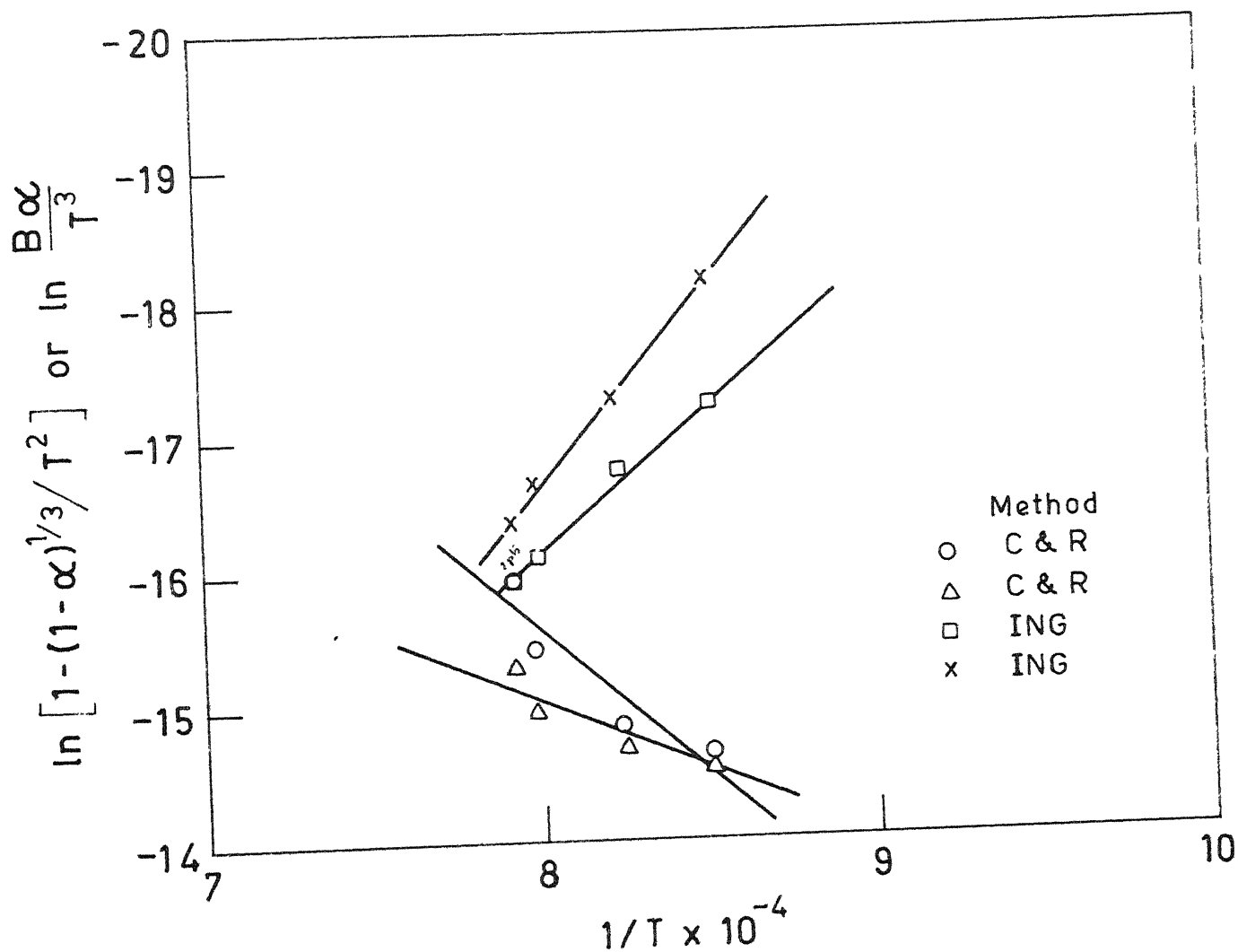


Fig. (28) TYPICAL PLOTS FOR EQUATIONS OF COATS + REDFERN AND INGRAHAM FOR CALCULATION OF ACTIVATION ENERGY.

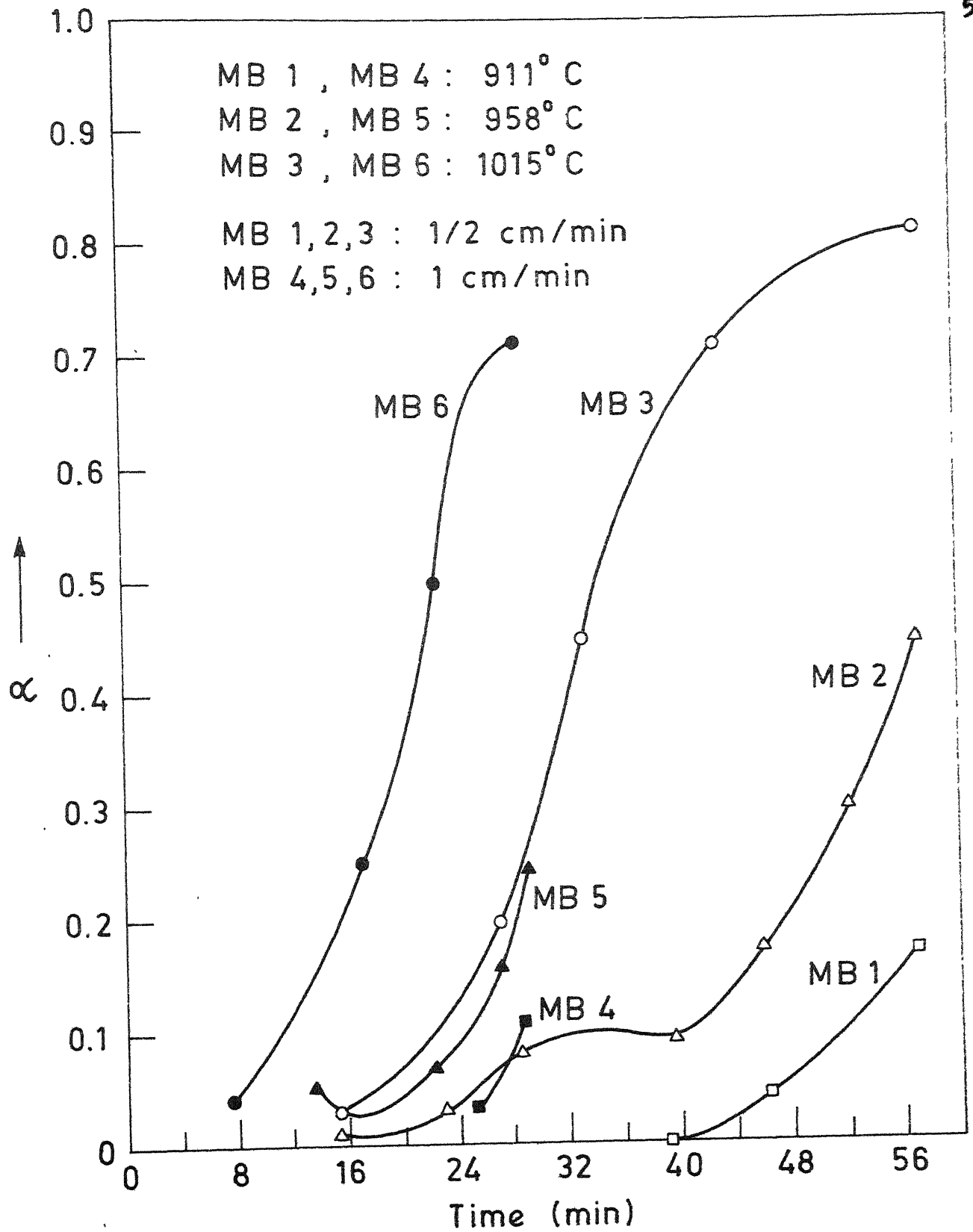


Fig. (21) α - TIME PLOTS FOR MOVING BED EXPERIMENTS ON CALCITE.

$$\alpha = \frac{44 - \text{pct LOI}}{44} \dots (15)$$

At lower speed of bed, the materials will reach the high temperature zone after a longer period and hence α -t plot will shift to right as shown in fig. (21). As can be expected α -t plots shift to left with increase in the furnace temperature. These α -t plots may be further converted to α -T (temperature $^{\circ}\text{K}$) plots for comparison with corresponding plots of DTA/TG experiments in fig.(22).

Calcite samples in such experiments decompose to any appreciable extent only near the entering end of the bed and the volume elements at some distances away practically remain undecomposed ($\alpha < 10$ pct.). The length of the bed where appreciable amount of decomposition occurs increases with increase in furnace temperature. In all these cases, complete decomposition of calcite material did not occur even at the entering end. Degree of decomposition decreased markedly with increasing distance from the end. This phenomenon may be occurring due to following reasons.

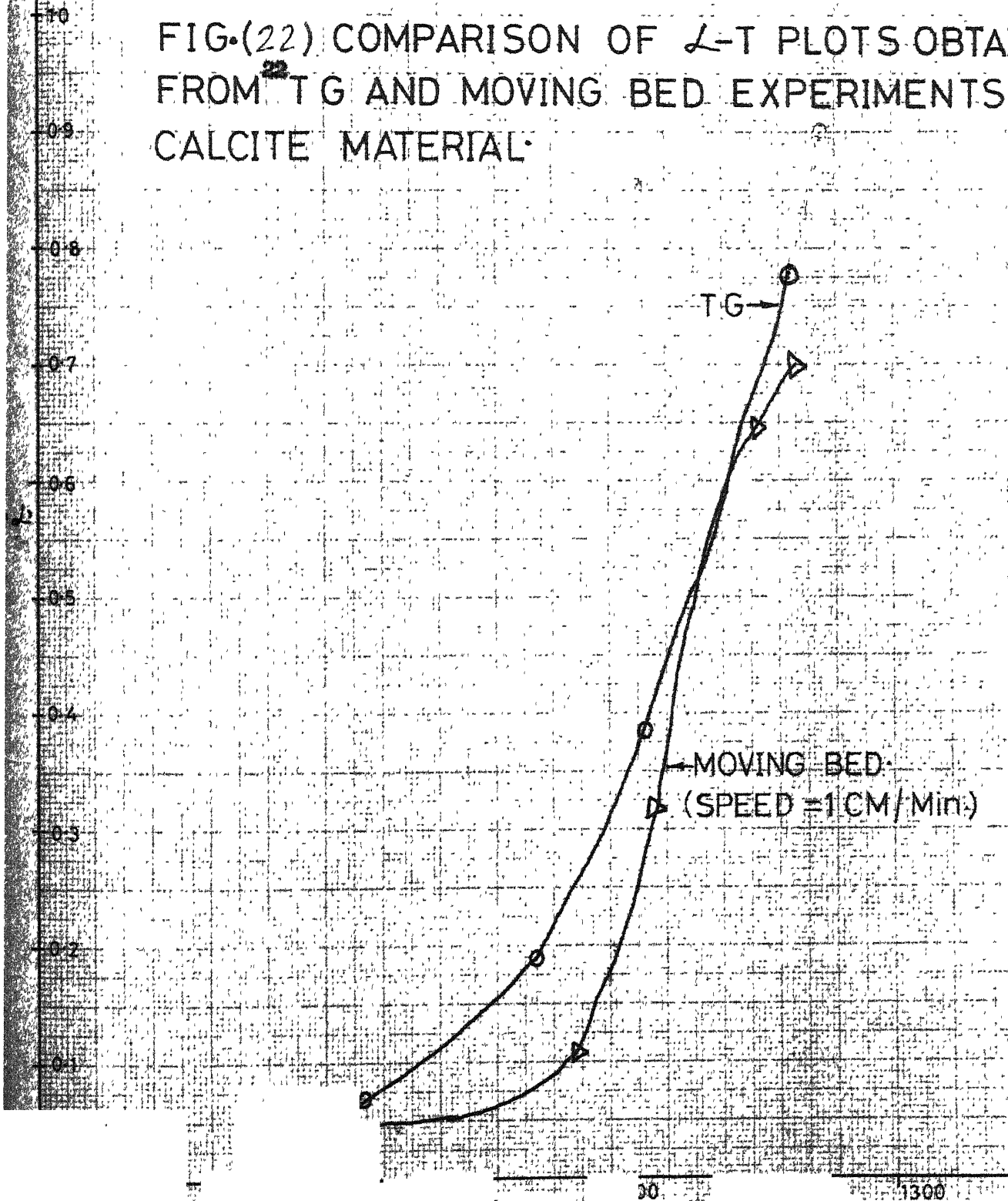
1. Slow rate of calcite decomposition
2. Insufficient heating of bed length.
3. Retarding of decomposition by CO_2 evolved.

Experimental results on temperature measurements inside the bed and CO_2 evolution measurements give more information on the behaviour of calcite decomposition.

Fig.(23) and (24) described the variation of temperature along the length of a moving bed at any time for limestone and

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FIG.(22) COMPARISON OF \angle -T PLOTS OBTAINED FROM TG AND MOVING BED EXPERIMENTS FOR CALCITE MATERIAL.



calcite. It is found that a steep temperature gradient prevails in the bed (moving at 1 cm/min) during the first twenty minutes of the experiment.

Since the decomposition temperature of calcite exceeds 900°C , only a small fraction in the bed will be decomposed within the duration of experiment. Actual rate of decomposition at any temperature will be further effected by variables such as nature of material, particle size, partial pressure of CO_2 etc. These factors have been separately studied on CO_2 evolution experiments described in Table III-3. Fig.(25) shows the effect of particle size for calcite and fig.(26) shows the effect of temperature for limestone and dolomite materials on rate of decomposition.

Experimental results on CO_2 evolution show the rate of decomposition is not markedly affected by partial pressure of CO_2 or particle size in the range studied in the present investigation. Retardation by CO_2 cannot account for steep α -t plots on moving bed experiment. It can be attributed only due to slow picking up of temperature by the bed and slow rate of calcite decomposition. Similar experiments with commercial limestone and dolomite sample show marked increase in the rate of decomposition [fig.(27)] and they should result in greater degree of dissociation in the moving bed. It may also be noted that actual temperature of calcite, limestone or dolomite sample in the bed is much less than the furnace temperature, even when the whole mass is kept in the high temperature zone as shown by temperature measurements in static

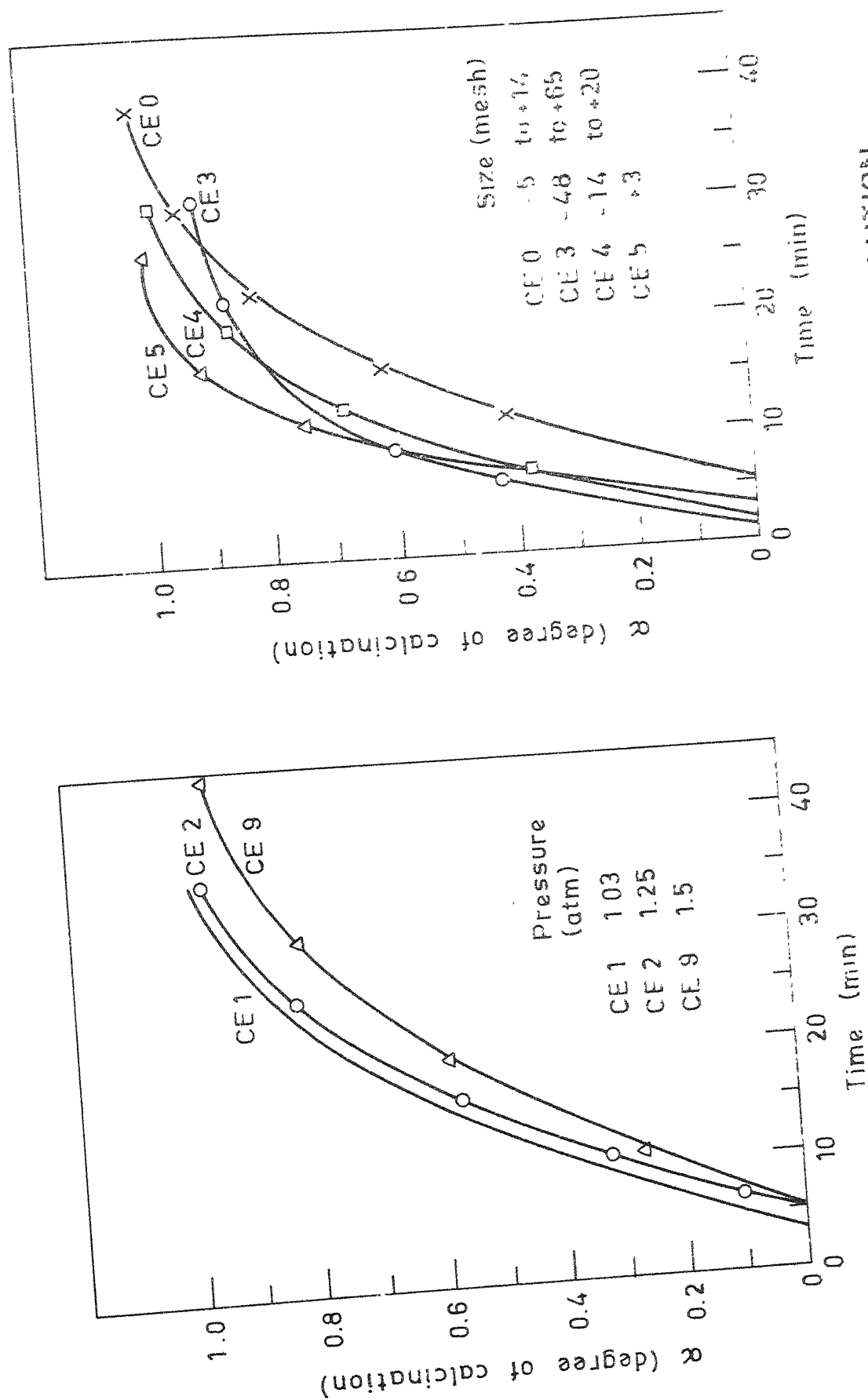


Fig. (25) α - TIME PLOTS FOR CALCITE IN CO_2 EVOLUTION EXPERIMENTS.

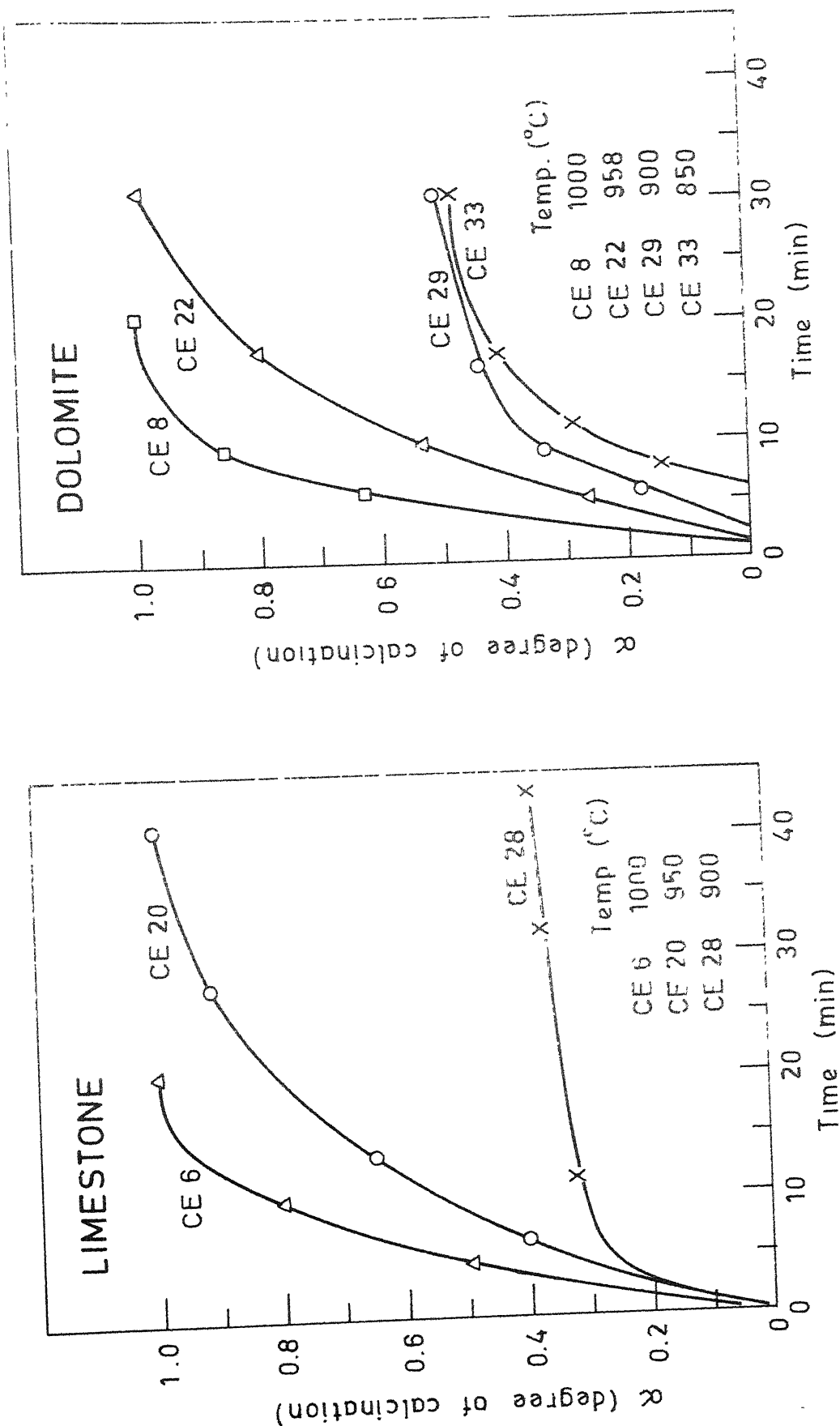


Fig. (26) EFFECT OF FURNACE TEMPERATURE ON α -TIME PLOTS FOR LIMESTONE AND DOLOMITE IN CO_2 EVOLUTION EXPERIMENTS.

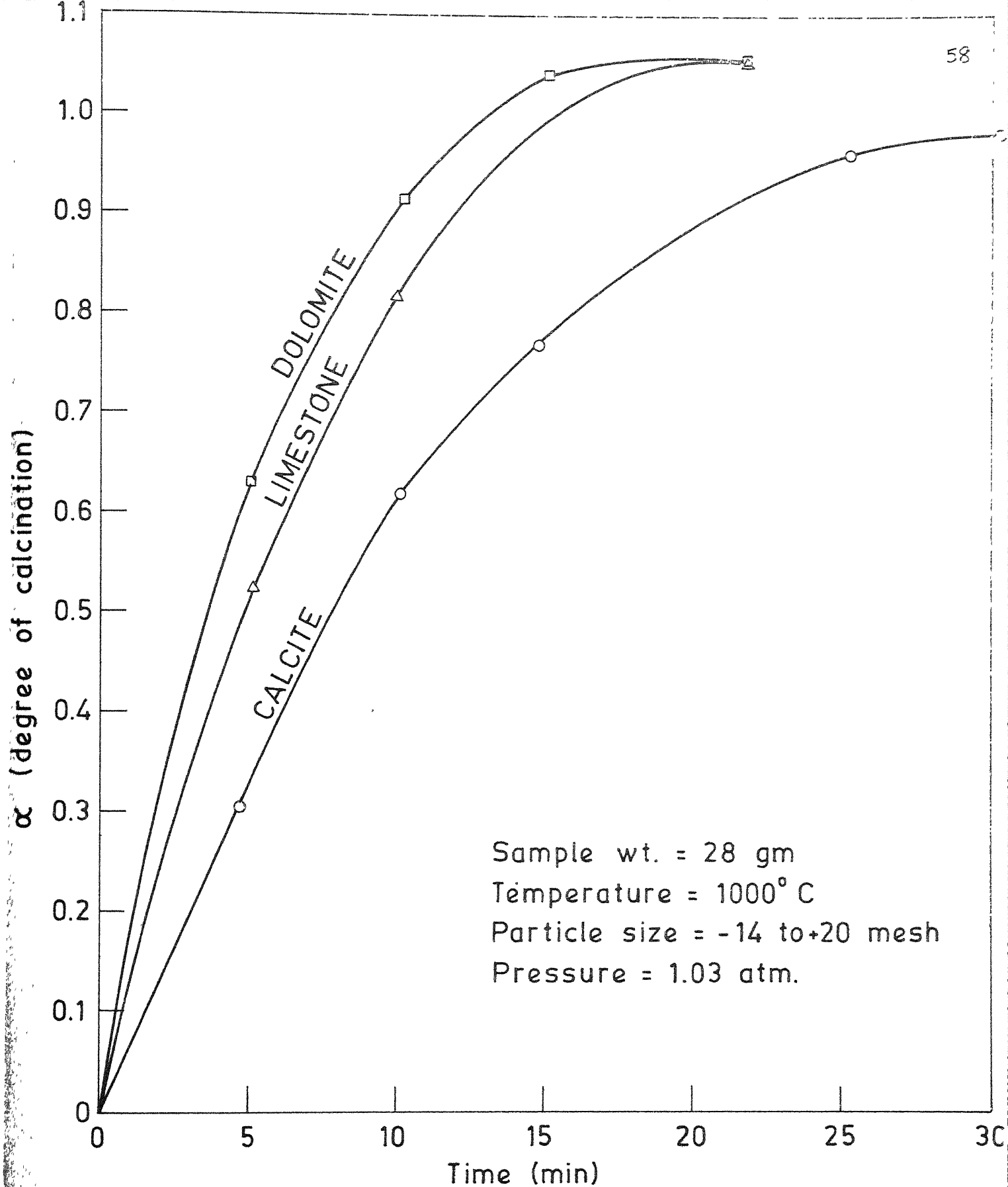


Fig. (27) α - TIME PLOTS FOR CALCITE, LIMESTONE AND DOLOMITE UNDER IDENTICAL CONDITIONS IN CO₂ EVOLUTION EXPERIMENTS.

bed experiments (TM1 to TM4). It will not be thus correct to calculate activation energy from $\alpha-t$ plots at different furnace temperatures. A simple heat balance model which predicts the temperature of the bed during its dissociation at any furnace temperature is described below.

5.4 Mathematical model for heating of carbonate materials in the Static bed :-

Let 'm' be the mass of the carbonate material and dm/dt is the rate of change of mass due to decomposition reaction, then from heat balance one can write,

$$\frac{d}{dt} \int_{298}^{T+273} (m, C_{p_s}) dT = hA(T_f - T) - \Delta H_R (-dm/dt) - \int_{298}^{T+273} C_p (-dm/dt) dT \quad (16)$$

where C_{p_s} is specific heat of solid and C_p is specific heat of CO_2 evolved, T is temperature in $^{\circ}C$, h is heat transfer coefficient in $Cal/cm^2 \cdot ^{\circ}C \cdot min$, ΔH_R is heat of decomposition reaction in (960 Cal/gm of CO_2 produced for $CaCO_3$ decomposition) T_f is furnace temperature in $^{\circ}C$, 'A' is surface area of solid material in the tube. In deriving equation(16), the sample is assumed to be uniform temperature throughout and it is kept in the constant temperature zone of the furnace.

Consider the case where the material is not decomposing

Case I :- $T < T_{reaction}$ and $dm/dt = 0$, and taking specific heat to be constant for samples,

$$mC_p dT/dt = hA(T_f - T) \quad \dots\dots(17)$$

Rearranging and integrating the equation(17)

$$\int_{T_A}^{T_f} \frac{dT}{T_f - T} = \int_0^t \frac{hA}{mC_p} dt \quad \dots\dots\dots(18)$$

$$\ln \frac{T_f - T_A}{T_f - T} = \frac{hA}{mC_p} t \quad \dots\dots\dots(19)$$

T_{reaction} is 900°C for calcite material. T_{reaction} will be lower for material like limestone and dolomite which contain MgCO_3 .

Value of 'h' for heating of material in a furnace has been reported to be* $0.16 \text{ Cal/cm}^2 \cdot ^\circ\text{C} \cdot \text{min}(\text{AppA})$. Values of m, A, C_p , T_f and T_A are known from experimental conditions.

Results of calculation show that 25 gm of calcite material in the tube will get heated to decomposition temperature of 900°C in $1\frac{1}{2}$ minutes when kept inside the furnace at 1000°C . This agrees with the results of actual temperature measurement in the static bed in fig.(16).

Limestone and dolomite materials contain a fraction of MgCO_3 which decompose at temperature lower than 900°C . The rate of heating will be less due to endothermic decomposition of MgCO_3 in such cases as dm/dt cannot be neglected any more in equation(17). Value of dm/dt depends upon the amount of undecomposed material left in the tube as well as on temperature of material. Since temperature changes with time, this is essentially a case of non-isothermal decomposition which is discussed below.

Case II : $T > T_{\text{reaction}}$, $dm/dt = f(T, \text{carbonate mass left})$

Assuming specific heats of species to be constant at temperature, equation(16) can be rewritten as,

$$mC_{p_s} \frac{dT}{dt} + C_{p_s} T \frac{dm}{dt} = hA(T_f - T) - \Delta H_R \left(\frac{-dm}{dt} \right) + C_{p_c} \left(\frac{dm}{dt} \right) T \quad \dots\dots\dots(20)$$

* (see Appendix A)

If the sample undergoes little temperature change for a retine, then one can write, $dT/dt \approx 0$ and,

$$dm/dt = - hA(T_f - T)/\Delta H_d + [Cp_L - Cp_S]T \quad \text{eq. (21)}$$

From equation (21) it follows that materials having high rate of decomposition should attain a lower value of constant temperature than materials which decompose at slow rate. Temperature measurements results for calcite, limestone and dolomite given in fig.(16) agree with this model. The critical results of constant temperature calculations for different values of dm/dt from equation (21), neglecting $[Cp_{CO_2} - Cp_S]$ value as very small, are given Table V-3.

If actual value of $\frac{dm}{dt}$ is less than the value given in Table V-3 for a certain temperature dT/dt is going to be positive [from equation (19)]. In other words temperature of the material will keep rising with corresponding increase in $|dm/dt|$ till a constant temperature is attained. As a large fraction of material decomposes $|dm/dt|$ will decrease and there will be again rise in temperature of the sample.

For calcite, the measured rate of decomposition of 0.4 to 0.6 gm/min i.e. 4-6 cc of CO_2 /sec correspond to sample temperature of $910^\circ C$ to $950^\circ C$ from Table V-3. In actual practice the temperature of the sample keep rising at a slow rate as clear from fig.(16) in the temperature range of $950^\circ C$ to $970^\circ C$. Source of discrepancy may be in the assumed value of heat transfer coefficient as $0.16 \text{ cal/cm}^2 \cdot ^\circ C \cdot \text{min}$. For limestone and dolomite

*(see Appendix - B)

T A B L E V-3

CALCULATIONS OF CONSTANT TEMPERATURE IN STATIC BED
FOR DIFFERENT RATE OF CARBONATE DECOMPOSITION

$$T_f = 1000^{\circ}\text{C}$$

| dm/dt gm/min | Theoriti- cal flow rate(cc/sec | Calculations for CaCO_3 | | Calculations for MgCO_3 | |
|-----------------|--------------------------------------|----------------------------------|-----------------------|----------------------------------|-----------------------|
| | | $T_f - T$ | $T(^{\circ}\text{C})$ | $T_f - T$ | $T(^{\circ}\text{C})$ |
| 0.05 | 0.5 | 8 | 992 | 5 | 995 |
| 0.10 | 1.0 | 13 | 987 | 7 | 993 |
| 0.20 | 1.9 | 27 | 973 | 15 | 985 |
| 0.30 | 2.8 | 41 | 959 | 24 | 976 |
| 0.40 | 3.7 | 54 | 946 | 31 | 969 |
| 0.50 | 4.7 | 68 | 932 | 39 | 961 |
| 0.60 | 5.6 | 82 | 912 | 47 | 953 |
| 0.70 | 6.5 | 95 | 905 | 55 | 945 |
| 0.80 | 7.5 | 109 | 891 | 61 | 959 |
| 0.90 | 8.4 | 123 | 871 | 71 | 929 |
| 1.00 | 9.3 | 136 | 864 | 78 | 922 |

presence of MgCO_3 will also affect the heat balance calculations due to its lower value of heat of decomposition i.e. 24.25 Kcal/mole compared to 42.5 Kcal/mole of CaCO_3 decomposition. At the same temperature of sample, higher rates of decomposition of MgCO_3 can be obtained than predicted for CaCO_3 as shown in Table V-3. Calculated temperature values compare well with the measured values.

When practically all carbonates have decomposed $\frac{dm}{dt}$ will again be zero and equation(19) will describe the further rise in temperature of the sample. Calculations show that the calcine limestone or dolomite sample will get heated from a temperature of 910°C to 990°C in 1 minute. Details are given in Table V-4. In actual practice it takes much larger time of 6 to 8 minutes because there will be a small fraction of carbonate material decomposing even at temperature higher than 910°C and it will consume heat in the process.

T A B L E V-4

DETAILS OF CALCULATIONS FOR HEATING OF DECOMPOSED
SAMPLE IN THE FURNACE

| | | |
|--------------------------------|---|---|
| Specific heat $C_{p_{CaO}}$ | = | 11.7 Cal/mole. $^{\circ}$ C |
| | = | 0.21 Cal/gm. $^{\circ}$ C |
| Surface area(A) of the Sample | = | 43.96 cm 2 |
| Initial mass | = | 25 gm |
| Decomposed mass(m) | = | 15 gm |
| Heat transfer co-efft. h | = | 0.16 Cal/cm 2 . $^{\circ}$ C.min |
| Temperature of furnace T_f | = | 1000 $^{\circ}$ C |
| Initial temp. of sample | = | 910 $^{\circ}$ C |
| Final temp. of sample T_A T | = | 990 $^{\circ}$ C |
| $\ln[T_f - T_A / T_f - T]$ | = | hAt / mC_p |
| $\ln[1000 - 910 / 1000 - 990]$ | = | $\frac{0.16 \times 43.96 \times t}{15 \times 0.21}$ |
| 2.2t | = | 2.2 |
| t | = | 1 min |

5.5 Model for heating of carbonate materials in Moving bed :-

It is possible to set up a simple heat balance equation for volume elements of length Δl , in the moving bed also. For any volume element at time t for Case I of no decomposition,

$$\pi r^2 \Delta l \rho C_p dT/dt = 2\pi r h \Delta l (T_f - T) \quad \dots\dots(22)$$

where r is the radius of tube, ρ is bulk density of the sample, T_f is the temperature of furnace corresponding to the volume element. Temperature is assumed to be constant across the cross section of tube and conduction terms in the axial direction are neglected.

Simplifying equation (22) $\frac{dT}{T_f - T} = \frac{2h}{r \rho C_p} dt \quad \dots\dots\dots (23)$

Therefore,

$$\int_{T_0}^T \frac{dT}{T_f - T} = \frac{2h}{r \rho C_p} \int_0^t dt$$

$$= 2ht/r \rho C_p \quad \dots\dots\dots(24)$$

For stationary beds, the left hand integral could be easily evaluated because T_f was constant. For a* temperature T_f is not constant but varying according to the temperature profile of the furnace. The integral can be evaluated if the variation of T_f is precisely known. If the bed is moving at the uniform velocity v , then

$$v = x/t \quad \dots\dots\dots(25)$$

where x is the distance covered in time t . The temperature profile of the furnace may be expressed in the following form,

$$T_f = T_0 + (T_m - T_0)(1 - \exp - jx) \quad \dots(26)$$

where T_0 is the temperature of the furnace mouth. T_m is maximum temperature of furnace and j is a constant. This shows that the evaluation of the left hand side integral in equation (24)

*volume element in a moving bed, the surrounding furnace)

would be somewhat complicated.

Calculations are further complicated in Case II where decomposition of limestone is also occurring, CO_2 gas so evolved passes through the rest of the bed and affects the overall heat balance in the volume element. The exact analysis for decomposition of carbonates in the moving bed are therefore not carried out in this thesis.

CHAPTER VI

CONCLUSION

It is shown that thermal analysis (simultaneous measurement of DTA, TG and DTG) can be used for reliable characterization in terms of the mineralogical composition and impurity content of the carbonate samples. DTA of dolomite indicates two endothermic peak corresponding to sequential decomposition of MgCO_3 and CaCO_3 . The MgCO_3 peak in dolomite however occurs at a temperature (800°C) higher than that associated with pure MgCO_3 (550°C). The TG data for the non-isothermal decomposition of carbonate has been analyzed to obtain the kinetic parameters for the reaction mechanism. Calculated values of activation energy around 39 Kcal/mole are comparable with the reported value of 40.5 Kcal/mole in the literature.

2. In the moving bed experiments, calcite material decomposes to any appreciable extent only at the entry of the entry of the bed only and degree of dissociation decreases markedly with distance away from that end. This phenomenon is explained due to temperature variation in the bed.

3. A technique of measuring the flow of CO_2 gas evolved during decomposition reaction under controlled temperature and pressure has been developed in the present work. It has been shown that limestone and dolomite materials dissociate much faster than calcite material under identical conditions of temperature and pressure. CO_2 pressure in the range of 1 to 1.5 atm.

and the particle size in the range from -3mesh to +65mesh did not seem to affect the rate of decomposition of calcite.

4. Actual measured temperature of calcite, limestone and dolomite samples in static bed experiments are always less than the furnace temperature. Heating of these materials in the furnace is characterized by an attainment of nearly constant temperature for some time. Constant temperature value for limestone and dolomite samples are much less than the temperature of the calcite samples. A heat balance model has been developed to correlate the temperature of the bed with the rate of decomposition of the carbonate material and the results have been confirmed by actual measurement of temperature in the static bed as well as in the moving bed.

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A P P E N D I X - A

CALCULATION OF HEAT TRANSFER COEFFICIENT FOR HEATING OF CARBONATE MATERIALS IN THE FURNACE

It is given in reference[14] that the value of heat transfer coefficient for heating of bricks in the furnace at 1000°F is $10 \text{ Btu/hr.ft}^2.^{\circ}\text{F}$. This value includes the contribution due to convection as well as due to radiation. In the present work temperature of furnace is 1000°C or 1830°F . Contribution due to radiation is going to be more and the value of 'h' will increase

$$h = h_c + h_r$$

Taking h_c as $5 \text{ Btu/hr.ft}^2.^{\circ}\text{F}$ and h_r as $5 \text{ Btu/hr.ft}^2.^{\circ}\text{F}$ at 1100°F , h_r value at 1830°F can be calculated as follows,

$$\begin{aligned} h_r(1830)/h_r(1100) &= [1830+460/1100+460]^3 \\ &= 3.0 \\ h_r(1830) &= 3 \times 5 = 15 \text{ Btu/hr.ft}^2.^{\circ}\text{F} \\ h(1830) &= h_c + h_r \\ &= 5 + 15 = 20 \text{ Btu/hr.ft}^2.^{\circ}\text{F} \\ &= 0.16 \text{ Cal/cm}^2.^{\circ}\text{C} \end{aligned}$$

This value is only approximate in nature and in actual practice it will vary with temperature of sample as well as with the presence of CO_2 in the tube.

A P P E N D I X - B

DETAILS OF SPECIFIC HEATS OF SPECIES OF INTEREST
IN THE PRESENT WORK [15]

| Species | $C_p = a + bT - cT^2$ (cal/mole. °K) | | Cp in cal/gm. °C | | | | | |
|-------------------|---|-----------------|--------------------|-------|-------|-------|-------|-------|
| | a | $b \times 10^3$ | $c \times 10^{-4}$ | 100°C | 300°C | 500°C | 700°C | 900°C |
| CO ₂ | 10.57 | 2.10 | 2.06 | 0.22 | 0.25 | 0.27 | 0.28 | 0.29 |
| CaO | 11.67 | 1.08 | 1.56 | 0.20 | 0.21 | 0.22 | 0.23 | 0.23 |
| CaCO ₃ | 24.98 | 5.24 | 6.20 | 0.22 | 0.26 | 0.28 | 0.29 | 0.31 |
| MgO | 10.18 | 1.74 | 1.48 | 0.24 | 0.27 | 0.28 | 0.29 | 0.30 |
| MgCO ₃ | 18.62 | 13.80 | 4.16 | 0.25 | 0.30 | 0.34 | 0.38 | 0.41 |

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